THE UNIVERSITY OF ALBERTA

NATURE AND GENESIS OF CAYMANITE IN THE OLIGOCENE-MIOCENE BLUFF FORMATION OF GRAND CAYMAN ISLAND, BRITISH WEST INDIES

by

E. B. LOCKHART

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Supervisor

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Date... April 15, 1996 ...

ABSTRACT

Caymanite is a laminated, multicoloured dolostone, which was deposited as a cavity filling sediment in the Oligocene-Miocene Bluff Formation, on Grand Cayman Island. Cavities and caverns, formed by karst processes and the leaching of fossils, were filled by sedimentation from moving water in the vadose zone. During deposition, sedimentary structures, including cross- and parallel laminations and channels, were formed. Anhedral dolomite is the main constituent of caymanite, while the coloured laminae also contain manganese, iron, nickel and copper. The dolomite was probably derived from the fine grain size fraction of swamp sediments, and was brought into the cavities by high volumes of sea and rainwater.

The metals were derived from the terra rossa soils and were transported into the cavities by groundwaters percolating down through the host dolostone. Once in the cavities, the metallic elements were oxidized by, and precipitated onto spheroidal and elongate bacterial colonies. The manganese mineralization has pigmented laminae black and grey, and iron mineralization has pigmented laminae red and orange.

Hurricane and storm seasons are possible periods during which caymanite might have been deposited, thus caymanite formation was probably a long, continuous process.

ACKNOWLEDGEMENTS

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Finally, my husband Tony Fogarassy is gratefully acknowledged for his encouragement and unfailing support.

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I. INTRODUCTION

A. LOCATION AND TECTONICS

Grand Cayman Island is 250 km south of Cuba, 280 km north-northwest of Jamaica, and 100 km west-southwest of Cayman Brac and Little Cayman Islands (Fig. 1). The island is on the Cayman Ridge which forms the northern wall of the seismically active Cayman Trench (Perfit and Heezen 1978, p. 1156). The Cayman Islands are part of a dynamic geologic system since the trench forms part of the boundary between the North American and Caribbean plates (Pinet 1971; Pinet 1972; Ballard 1976; Perfit and Heezen 1978). The northern trench walls are experiencing left lateral strike-slip movement (Perfit and Heezen 1978, p. 1156). The Cayman Ridge has been subsiding since the Miocene, previously it was a "... shallow carbonate bank..." (Perfit and Heezen 1978, p. 1172). The Cayman Islands, Jamaica and much of southern Cuba, however, have undergone localized uplift since the middle Miocene (Matley 1926; Perfit and Heezen 1978, p. 1172). Diagenetic evaluation of the dolostone of the Bluff Formation by Jones *et al.* (1984) also indicates recent uplift of the island.

B. CLIMATE

The climate on Grand Cayman Island is affected by the Tradewinds, which are predominantly from the east (Sauer 1982). The Cayman Islands are described as a "...crossroads for cyclones generated both in the North Atlantic and within the Caribbean" (Sauer 1982, p. 2), hence cyclones occur on the islands at least once per decade. These storms greatly disrupt vegetation and any rock and sediment which is poorly lithified or loosely attached to its substrate.

The average temperature in summer is 28°C and in winter 24°C. Precipitation is at its lowest between December and April; between May and November is a rainy season. The southwestern part of the island has higher annual rainfall (150-165 cm/year) than the rest of the island (which averages 125 cm/year)(Sauer 1982).

Tectonic data do not indicate major movement of Grand Cayman Island during or after the Miocene (Perfit and Heezen 1978). Therefore it is likely that the island has been under the same climatic conditions since the formation of caymanite.

C. KARST TOPOGRAPHY

The karst topography developed on the Bluff Formation of Grand Cayman Island involves a complex array of sinkholes, joints, and razor-edged phytokarst pinnacles. The Bluff Formation has a consistently developed (rather than patchily developed) rainwater solution karst system which has produced cracks, caves, cavities, and fissures. Joints have been enlarged, and some leaching of fossils has occurred. Phytokarst (Fig. 2a), which is prominent at Hell and Cayman Kai (Fig. 3), is produced by the boring and

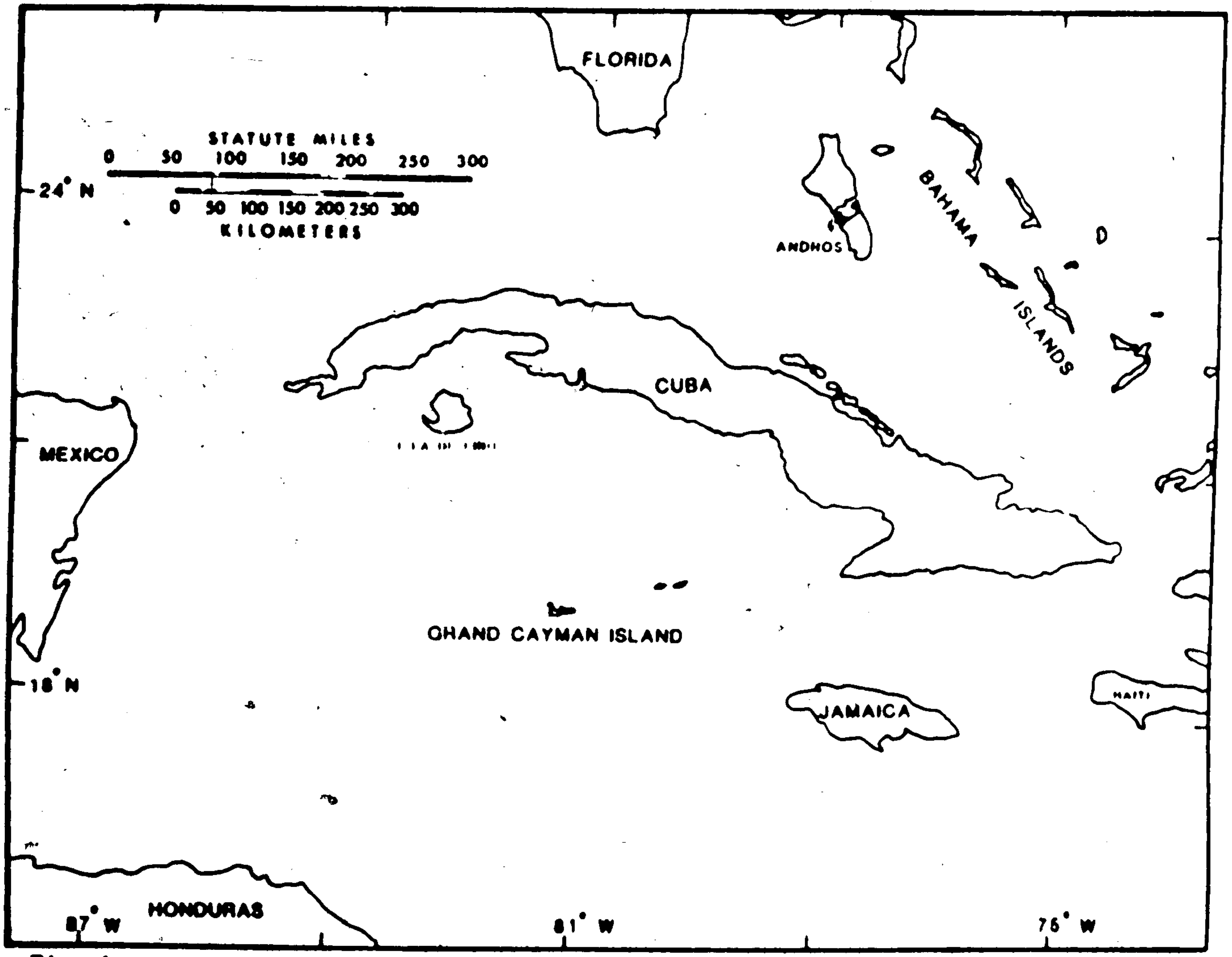


Fig. 1. Location map of Grand Cayman Island.

Figure 2

Figure 2a: General view of phytokarst at Hell showing the blackened pinnacles of dolostone of the Bluff Formation. The areas between the pinnacles are filled with unconsolidated organic-rich sediment that has a high-water content. Photograph courtesy of B. Jones.

Figure 2b: Example of a smooth-walled cavity in the Bluff Formation which probably resulted from dissolution of the dolostone rather than leaching of skeletal material. Stalagmites and red clay occur in the cavity.

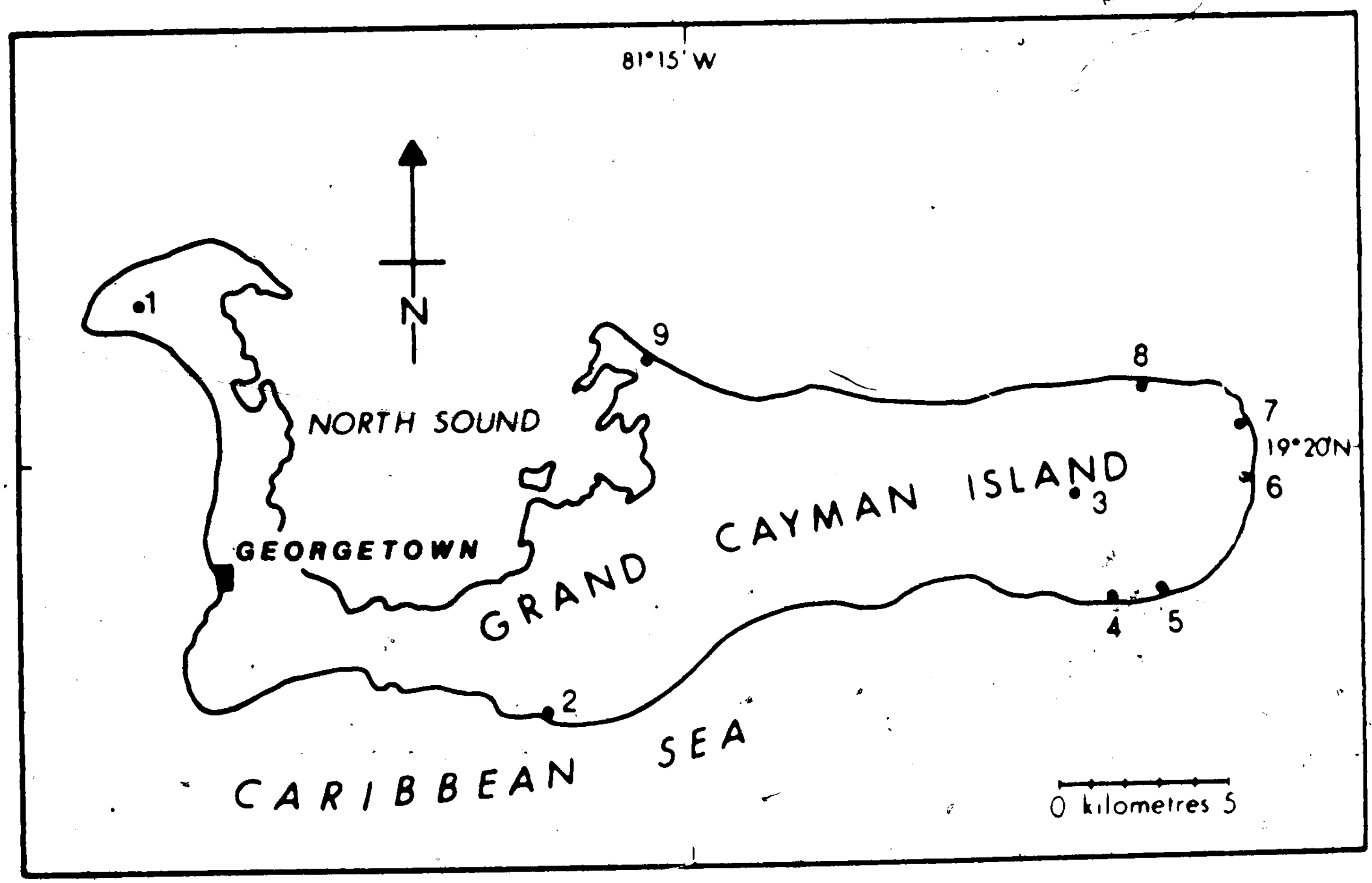
Figure 2c: Example of elongate cavities created by leaching of coral skeletons. The "strands" in each cavity are micrite-filled borings that were developed in the original corals but not affected by later dissolution. Red clay coats the walls.

Figure 2d: Caymanite filling a leached coral. Note the cross-laminations as well as the relationship between the colours of the various laminae.


a
c
1.5cm
d
2cm

Figure 3

Map of Grand Cayman Island showing sample localities referred to in text. (1) Hell, (2) Pedro's Castle Quarry, (3) High Rock Quarry, (4) Blowholes, (5) East End, (6) Collier's Bay, (7) Tortuga Club, (8) Great Bluff and (9) Cayman Kai.


81°15' W
N
NORTH SOUND
GEORGETOWN
GRAND CAYMAN ISLAND
CARIBBEAN SEA
19°20'N
1
2
3
4
5
6
7
8
9
0 kilometres 5

solution action of algae and fungi. It is distinctive because of the "...black coated, jagged pinnacles marked by delicate, lacy dissection that lacks any gravitational orientation..." (Folk *et al.* 1973, p. 2351).

D. GENERAL GEOLOGY

Various aspects of the geology of Grand Cayman Island have been described by Matley (1926); Doran (1954); Warthin (1959); Rehder (1962); Mather (1972); Brunt *et al.* (1973); Folk *et al.* (1973); Folk and McBride (1976); Emery and Milliman (1980); Emery (1981); Woodroffe *et al.* (1983) and Jones *et al.* (1984).

Grand Cayman Island is comprised of two formations (Fig. 4). The Oligocene-Miocene Bluff Formation (Matley 1926, p. 355) which is white on a fresh surface, comprises dense, crystalline, dolostone. It is sufficiently hard to sound metallic when struck with a hammer. Corals, algae, molluscs and foraminifera, although commonly leached to various degrees, are common in the Bluff Formation. This subhorizontally bedded dolostone probably originated as shallow water sediments (Matley 1926; Emery 1981).

Diagenesis of the Bluff Formation has been extensive (Folk *et al.* 1973; Jones *et al.* 1984) and includes dolomitization, partial and complete leaching of fossils, and on a microscopic scale, the formation of many phases of pore and cavity lining cements (Folk *et al.* 1973; Jones *et al.* 1984).

The diagenesis that altered the Bluff Formation did not affect the Ironshore Formation, which unconformably overlies the Bluff Formation (Brunt *et al*. 1973), and dominates the western part of the island (Fig. 4). Although the surface of the Ironshore Formation has been casehardened during subaerial exposure to form a calcrete crust (Warthin 1959, p. 649), the underlying rock is poorly consolidated. These rocks consist of "... poorly consolidated reef limestones, calcarenites of varying origins and lagoonal muds and sands..." (Brunt *et al*. 1973, p. 211).

The hydrogeology of the island has been documented and discussed by Mather (1972) and Bugg and Lloyd (1976). There are three freshwater lenses in the subsurface of Grand Cayman Island (Mather 1972, p. 157). One is near Pedro's Castle Quarry, a second is near High Rock Quarry, and the third is near East End (Fig. 3). Only the third and easternmost lens occurs exclusively in the Bluff Formation, while the first and second lenses occur in both the Bluff and Ironshore Formations. Freshwater diagenesis has affected, and is currently affecting the subsurface Bluff Formation (Mather 1972). These lenses are an important consideration because of the diagenetic effect they may have had on the dolostone of the Bluff Formation (Jones *et al*. 1984) or on caymanite.

Cavities and caves created either by diagenetic leaching, or by karst processes are common in outcrops of the Bluff Formation (Figs. 2b and c). The sizes of the caves

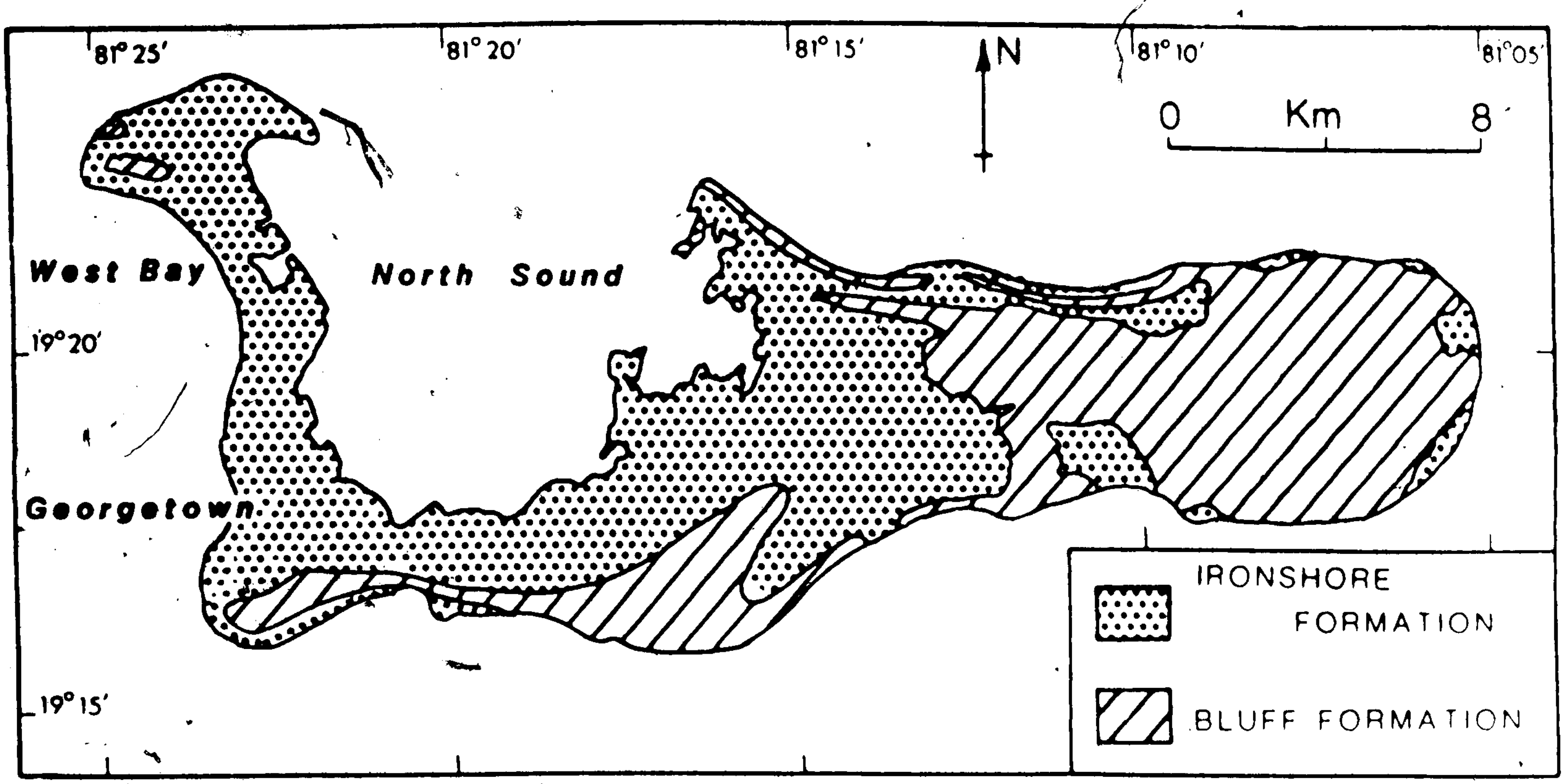


Fig. 4. Distribution of the Bluff Formation and the overlying Ironshore Formation on Grand Cayman Island. From Brunt <u>et al</u>. (1973).

and cavities are extremely variable, the smallest being less than one cubic centimetre. Some cavities are filled with a dense, multicoloured (black, grey, white, buff, orange, pink, and red) laminated dolostone, called caymanite (Fig. 5). Although caymanite occurs in less than one half of these cavities, it is the most common type of cavity fill. Other types of cavity fill are flowstone, stalagmites and stalactites, and more rarely, dolograinstone. Caymanite is less common in the inland localities (Fig. 3) than those along the coastline. Similarly, caymanite is more common in the eastern part of the island.

The term caymanite was coined because the Caymanian people cut and polish it to make semi-precious gemstone jewellery. The vivid colours and intricate sedimentary structures of the laminae make interesting and beautiful jewellery, and also pose enigmatic scientific questions. These problems are addressed in this thesis.

E. PREVIOUS WORK

The occurrence of caymanite has been documented by Folk *et al.* (1973); Folk and McBride (1976); Stoddart (1980); and Jones *et al.* (1984). Folk and McBride (1976, p. 666) suggested that caymanite might be a geopetal fill of solution channelways in the Bluff Formation. Stoddart (1980, p. 13) noted that caymanite has been found on Grand Cayman and Cayman Brac Islands but not on Little Cayman, and that it is "apparently a fissure-fill". In a jewellery shop on

Figure 5

Caymanite sample comprised of a minimum of six generations of brown and red laminae. Channels, channel filling laminae, variable grain sizes, geopetal filling (gp) are present. Generation 6 occupies a partially leached fossil. Sample courtesy of B. Jones.

4 cm

Grand Cayman Island, a note accompanying a display of caymanite jewellery suggested that caymanite is of volcanic sedimentary origin, although the shop owner could provide no further information. No written accounts of any similar cavity fill material are known to the author. One hotel in Cancun, Mexico, has slabs on the floor of its lobby which contain rocks identical to caymanite (B. Jones 1985, pers. comm.). Unfortunately, the origin of these rock slabs is not known.

F. OBJECTIVES

There is relatively little information regarding caymanite. Therefore, this thesis documents and considers:

1. the controls on the occurrence of caymanite in the Bluff Formation of Grand Cayman Island.
2. the chemical composition of caymanite, and its effects on the macroscopic form of caymanite, such as pigmentation.
3. the petrography of caymanite to assess its macroscopic composition.
4. the micropaleobiology of caymanite, and its effect on the macroscopic form of caymanite,
5. the environment of formation of caymanite: whether it was submarine, subsurface meteoric or subsurface vadose.
6. the method of sediment deposition or precipitation.
7. the overall geological significance of caymanite.

G. METHODS OF STUDY

Caymanite was examined:

1. In the field in order to document its megascopic features and its relationship to the host Bluff Formation. In all, nine localities were studied in detail (Fig. 3): seven in the coastal regions and two inland (Fig. 3).
2. In approximately 55 hand specimens to document macroscopic relationships between laminae of caymanite; to determine the presence of any colour sequences or structural relationships common to several deposits of caymanite; and to examine the types of cavities filled or partly filled by caymanite.
3. In 24 thin section to determine crystal and particle sizes; the interlaminae relationships; and the presence or absence of fossil fragments.
4. On the SEM, 16 samples, to determine mineralogy, crystal size, the structures of the bacterial remains, and to examine the particles which impart the pigmentation to the caymanite.
5. Whole rock analyses of different colours of six caymanite laminae provide an accurate list of the chemical compositions of caymanite.

H. LABORATORY METHODS

Caymanite was examined in handsample, thin section, and on the Scanning Electron Microscope (SEM). Selected samples of caymanite were chemically analysed by A. Stelmak.

Hand samples were collected in the field and, where possible, the way-up of the caymanite was marked on the sample. Most of the samples collected, however, were from boulders which resulted from dynamite blasting of the Bluff Formation during construction of the coastal Queen's highway, or during excavation of the two dolostone quarries (Fig. 3). The stratigraphic tops of these samples were not marked, although they can be extrapolated, in some cases, by examining the cut and fill structures that are present in some of the caymanite laminae.

Selected samples of caymanite and the host rock were cut into centimetre thick slabs. By examining these slabs, the three dimensional attitude of the laminae in the caymanite could be determined.

Preparation of thin sections of the caymanite using water caused glass slides to shatter. This problem was overcome by using kerosene as the cutting medium. The dolomite crystals in caymanite are generally 5-10μ (longest axis); thus dolomite crystals could conceivably be stacked six high in a standard 30μ thin section thick. This stacking of crystals made thin section examination of an individual crystal difficult, but by grinding the thin sections with 1000μ grit powder and thinning them to approximately 15μ, the optics improved markedly.

To highlight porosity, nine thin sections were impregnated with blue epoxy. The thin sections were stained with Alizarin Red Solution (Friedman 1959) which stains calcite red but does not affect dolomite.

Caymanite was examined with the SEM. Small fragments of red, white, and black caymanite were mounted onto SEM stubs and then coated with gold. Analysis of the constituent crystals of the caymanite was achieved by using an EDX analyser attached to the SEM. In this way it was possible to match compositional data with morphological data.

Whole rock analyses were carried out on two red, two white, and two black caymanite samples, and on the Bluff Formation dolostone. These are quantitative evaluations of the composition of caymanite, rather than the qualitative evaluations provided by thin section and SEM examination. The whole rock analyses were conducted for the following components: loss on ignition, calcium, magnesium, sodium, iron, manganese, potassium, nickel, aluminium, lead, copper and titanium. The dolostone of the Bluff Formation was analyzed for its manganese content. One terra rossa sample was analysed for calcium, magnesium, manganese, iron and aluminium.

Thin section photography was carried out using a Carl Zeiss polarizing photomicroscope. All of these photographs were taken with Kodak Panatomic X black and white film.

II. FIELD RELATIONSHIPS

A. RECOGNITION OF CAYMANITE

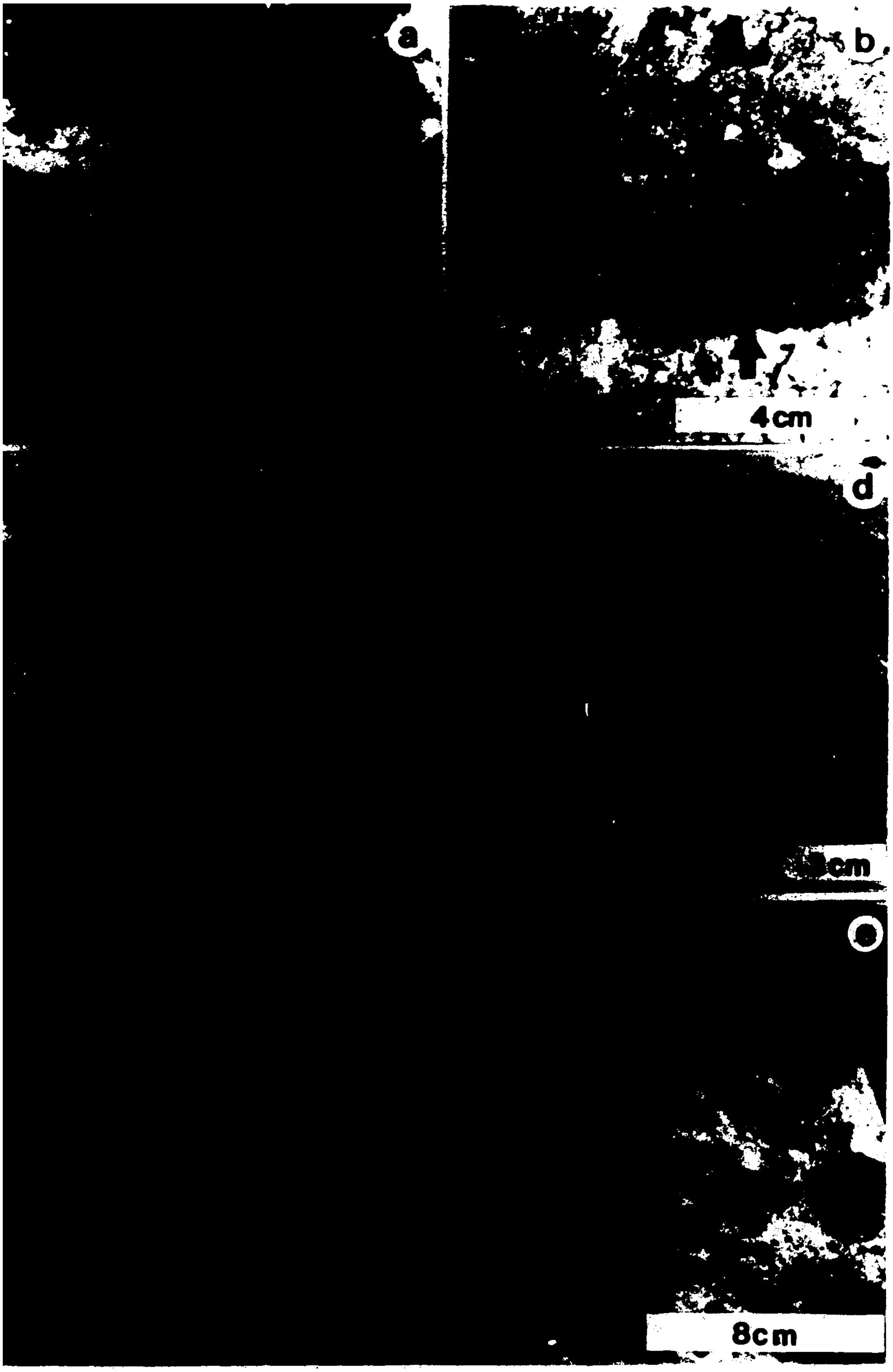
On weathered outcrop surfaces and those affected by phytokarst, caymanite can be difficult to recognize. With experience, however, it is possible to recognize such caymanite by the weathering patterns; the host rock is non-laminated while differential weathering commonly accentuates the laminations of the caymanite (Fig. 6c). At some localities the red and orange colours of the caymanite are sufficiently intense to be visible through the phytokarst. On freshly exposed outcrop surfaces, the textural and colour contrasts between the white host dolostone and the coloured caymanite highlights its occurrence.

B. GEOGRAPHIC OCCURRENCE

Caymanite has only been found in the dolostone of the Bluff Formation. Virtually all outcrops of the Bluff Formation were examined for caymanite. Most samples of caymanite came from exposures in the east and northeast parts of the island, and in particular from exposures close to the coastline (Fig. 3). Access to the centre of the island is difficult. The only exception is High Rock Quarry (Fig. 3) which provides excellent exposures of the Bluff Formation. Little caymanite, however, was found in this quarry. Despite the imposed geographic bias to the sample

Figure 6

Figure 6a: Three dimensional exposure of caymanite that highlights the lateral continuity of the laminae.
Figure 6b: Irregularly shaped cavity formed through the leaching of a coral, partly filled with caymanite.
Figure 6c: Example of a weathering surface in the Bluff Formation showing how differential weathering highlights the caymanite against the massive dolostone of the host formation.
Figure 6d: A cavity formed by dissolution, partly filled with caymanite. The beige and white laminae in this cavity are typical of the caymanite found in High Rock Quarry, Locality 3 (Fig. 3).
Figure 6e: Example of numerous small cavities in a small area, each filled with caymanite. The order of colours in each caymanite succession and the attitude of the laminae is different from cavity to cavity. Photo by B. Jones.


a
b
4cm
d
8cm

locations, caymanite would appear to be more common in coastal exposures of the Bluff Formation, such as at Cayman Kai, Pedro's Castle Quarry, Blowholes, East End, Collier's Bay, and Tortuga Club (Fig. 3).

Construction of the Queen's Road in 1981-1982 involved considerable blasting of the Bluff Formation. These fresh outcrops provided excellent exposures of the dolostone and the associated caymanite. The outcrops on the northeast and eastern parts of the island have the most brightly coloured caymanite on Grand Cayman Island. Where red and orange caymanite occur on the island, such as at East End, the locality typically has vegetation and terra rossa soil on the surface. Similarly, where no or rare orange and red laminae occur, little or no vegetation has inhabited the surface, such as at Hell or Cayman Kai. This, however, may be a false correlation because there is no guarantee that the vegetation patterns were the same when the caymanite actually formed.

C. STRATIGRAPHIC OCCURRENCE

Caymanite occurs in cavities that were created by the leaching of fossils, or by the dissolution of the host rock. These cavity forming processes could have been subject to a stratigraphic control, such as soluble strata, level of the water table, or the position of fossils in the original rock.

There is some evidence to suggest that there may be a stratigraphic control on the occurrence of caymanite. For example, at Pedro's Castle Quarry (Fig. 3) the number and size of cavities filled with caymanite apparently decreased with depth on the quarry walls. The workers at Pedro's Castle Quarry noted that caymanite is extremely rare in the Bluff Formation at depths greater than 10 m below the surface. Along the east and northeast parts of the island there is a wave cut notch in the Bluff Formation that is about 3 m above the level of the highway. The abundance of caymanite at the same approximate stratigraphic level, slightly below highway level, is striking. At Locality 8 (Fig. 3) there are large surface area exposures (each is approximately 3 m^2) of caymanite slightly below the level of the highway. These examples suggest that there may have been an element of stratigraphic control on the distribution of caymanite.

Some caymanite occurs in small cavities that appear to have a random distribution. Most cavities of this type were formed by the leaching of fossils. Their distribution is thus a function of the original depositional fabric of the Bluff Formation. This type of caymanite (Figs. 6b; 7; 8) is found at most localities around the island (Fig. 3).

Figure 7

Negative photographic print of thin section showing attitude of caymanite laminae in a cavity that was created by the leaching of a colonial coral. Tortuga Club, Locality 7 (Fig. 3). Arrow indicates the way-up of the sample. Note the highly variable angles associated with caymanite laminae.

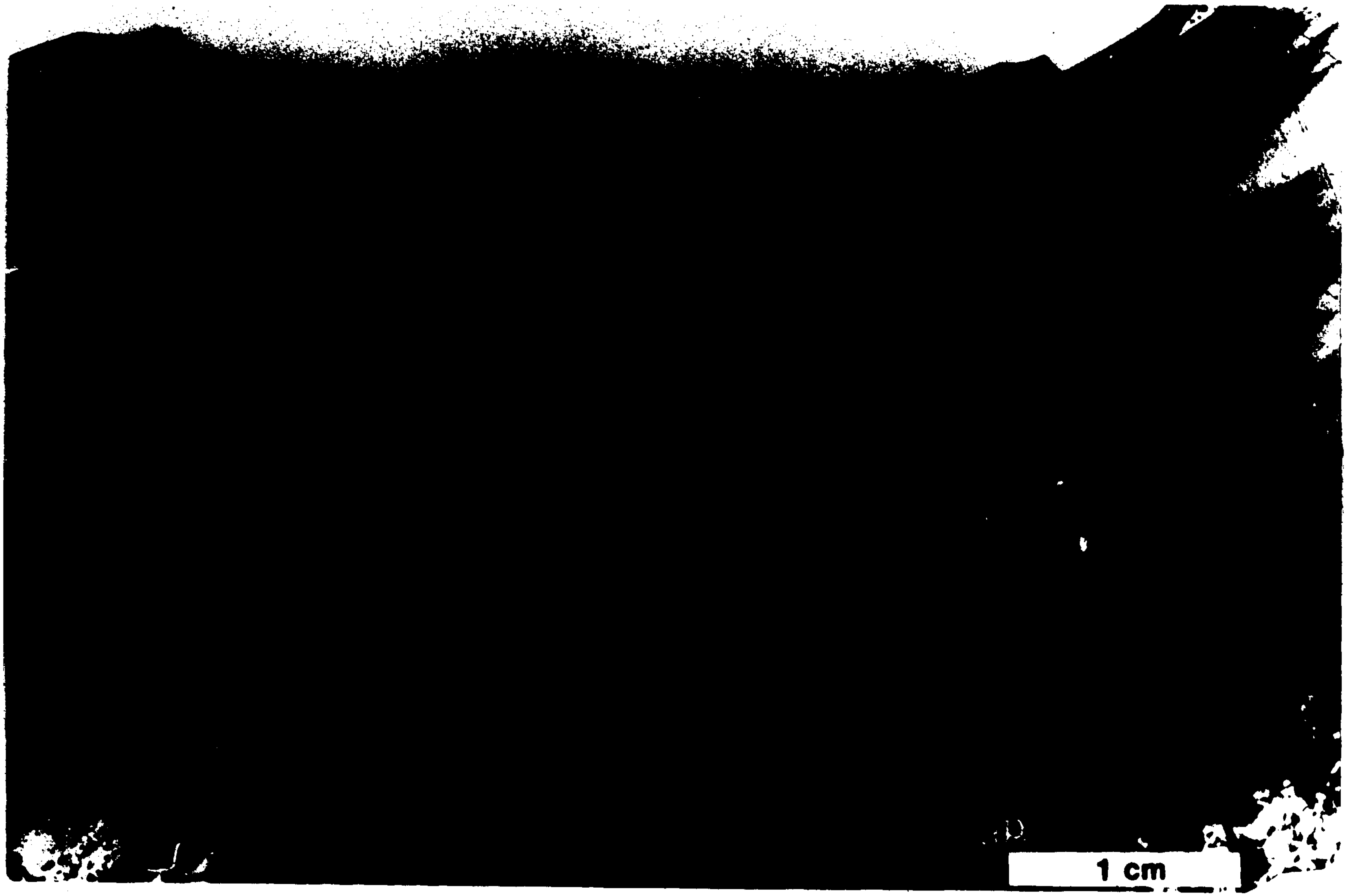

1 cm

Figure 8

Negative photographic print of a thin section showing caymanite formed in a cavity that was created by the leaching of a sclerosponge (open arrow). Note attitude of laminae and void (v) which was formed by dissolution of the caymanite. The scratches are from the original thin section. The solid black arrow indicates way-up. Tortuga Club, Locality 7 (Fig. 3).

D. DIMENSIONS AND SHAPE

Caymanite occurs in cavities as small as two millimetres and as large as two metres, longest axis. Voluminous caymanite occurred at Pedro's Castle Quarry where it occurred in a sheet that was 10 m long, and up to 1 m thick (Figs. 9, 10). There were also well exposed caymanite units on the northeast coast of the island. At Locality 8 (Fig. 3) the caymanite covers an area of 3 by 2 m. The largest single piece of caymanite observed (1.5 x 1.0 x 0.5 m) is in a jewellery shop at West Bay. Sequences with a maximum dimension (vertical or horizontal) greater than 1 m are rare. Some cavities hosting caymanite, whether randomly positioned leached fossils or stratigraphically controlled caves, are not completely filled with caymanite (Figs. 6b and d). This indicates that deposition of caymanite ceased to occur in those cavities, either because the transportation channels became blocked, or sediment was no longer available. This is important since it demonstrates the temporal aspect of the development of caymanite.

The boundary between the host rock and the caymanite is variable. A cavity created by the leaching of a fossil typically has a more irregular outline than one created by karst solution processes (Figs. 6b and d). Caymanite does not however, exhibit a preference for one type of cavity over the other. In both types of cavities, there is typically a thin (less than 1 mm thick) band of orange or beige dolomite (limpid dolomite) around the entire cavity

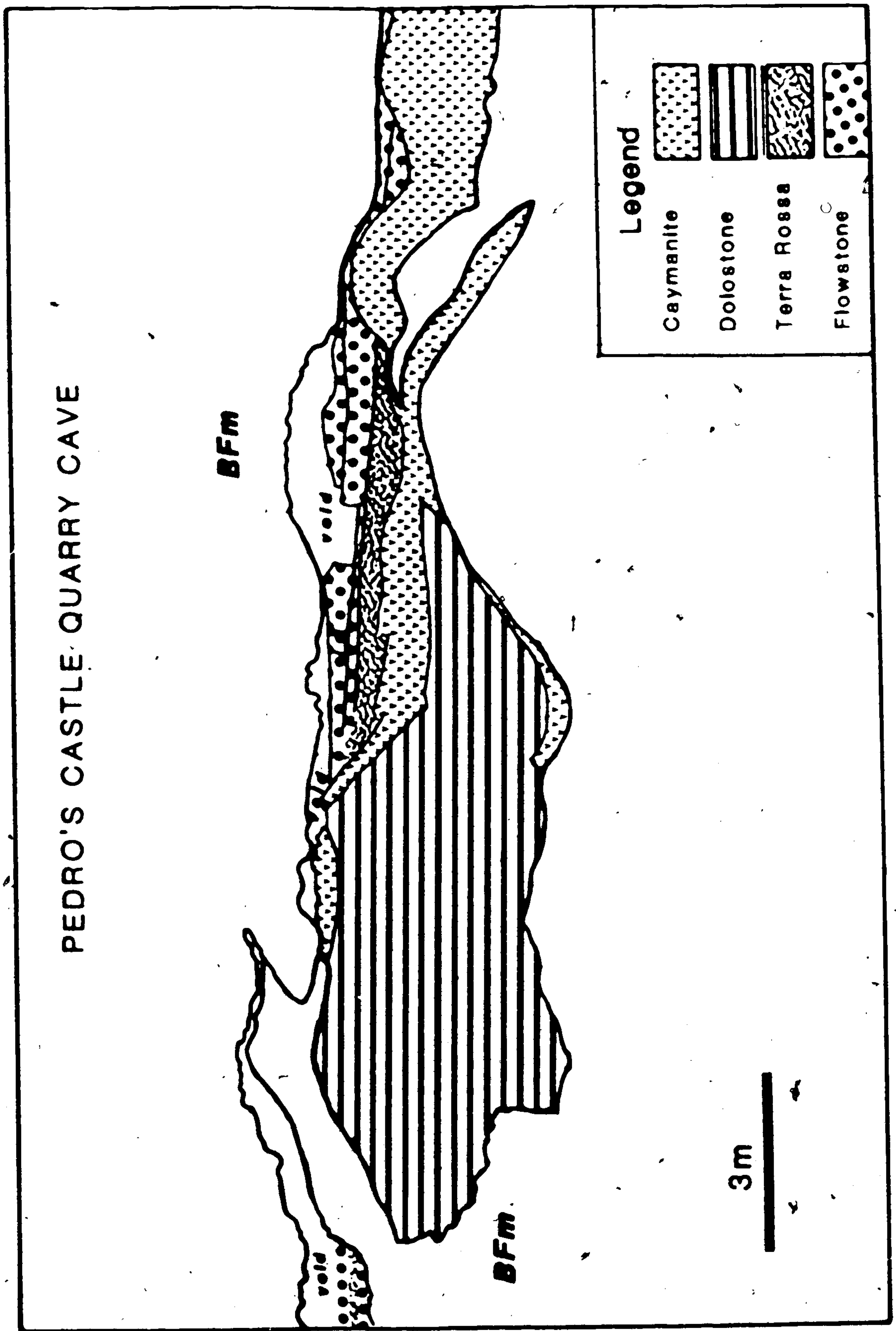
Figure 9

General view of an old cave developed in the Bluff Formation (BFm) at Pedro's Castle Quarry. The cave has been filled with a complex succession of caymanite (ct), flowstone (fs), terra rossa (tr) and dolomitic grainstone (ds).


1m

Figure 10

Sketch of cave in Pedro's Castle Quarry to accompany Figure 9, showing four types of cave filling material. Voids above the flowstone indicate that cave sedimentation ceased before the cave was entirely filled. BFm = Bluff Formation.


PEDRO'S CASTLE QUARRY CAVE
BFm
void
BFm
void
3m
Legend
Caymanite
Dolostone
Terra Rossa
Flowstone

wall which separates the host dolostone from the caymanite (Fig. 1'c).

E. THREE DIMENSIONAL EXPOSURES

At various localities on Grand Cayman Island there are three-dimensional exposures of caymanite. Such exposures are important because they allow determination of the three dimensional attitude of the laminae in the caymanite (Fig. 6a). To further understand the three-dimensional form of the caymanite laminae, large samples of caymanite were serially sectioned.

Cross bedded, variably thick and subhorizontally oriented laminae are common in caymanite. Cross bedding is seen among laminae which are several millimetres thick (Fig. 7), and the angles are low (2°, Fig. 7) while some are moderate (10°, Fig. 2d). In some samples, channels have been cut into laminae and subsequently filled in by younger caymanite (Figs. 12a - d). Channels represent an erosional period between depositional episodes. Channels were noted as narrow as 9 cm wide and 2 cm deep (Fig. 13a); and up to 1.2 m wide and 0.2 m deep (Fig. 14e). Superposition of laminae and channels upon previously deposited caymanite is evident in some samples (Figs. 12c, d). Changes in grain size can accompany transition from one lamina to an adjacent one. One sample, GC 83 435 (from Tortuga Club, Fig. 3), contains alternating laminae of coarse dolograinstone and caymanite. Finally, caymanite is characterized by its vividly coloured

Figure 11

Figure 11a: Distinctly coloured caymanite with one channel in upper part of sample. Channel is filled with caymanite. Colour changes abruptly between adjacent laminae. Pedro's Castle Quarry, Locality 2 (Fig. 3).

Figure 11b: Parallel caymanite laminae with coarse sand and pebble fragments of dolostone from the Bluff Formation. Great Bluff, Locality 8 (Fig. 3).

Figure 11c: Caymanite with very steep laminae dip angles. Note the thin orange band coating the cavity; this was formed prior to caymanite deposition. Sample from the east end of the island.

Figure 11d: Caymanite with manganese coated fragments of dolostone from the Bluff Formation. Black coating on pebbles does not continue below level of black lamina. Colour changes gradually between laminae. Great Bluff, Locality 8 (Fig. 3).

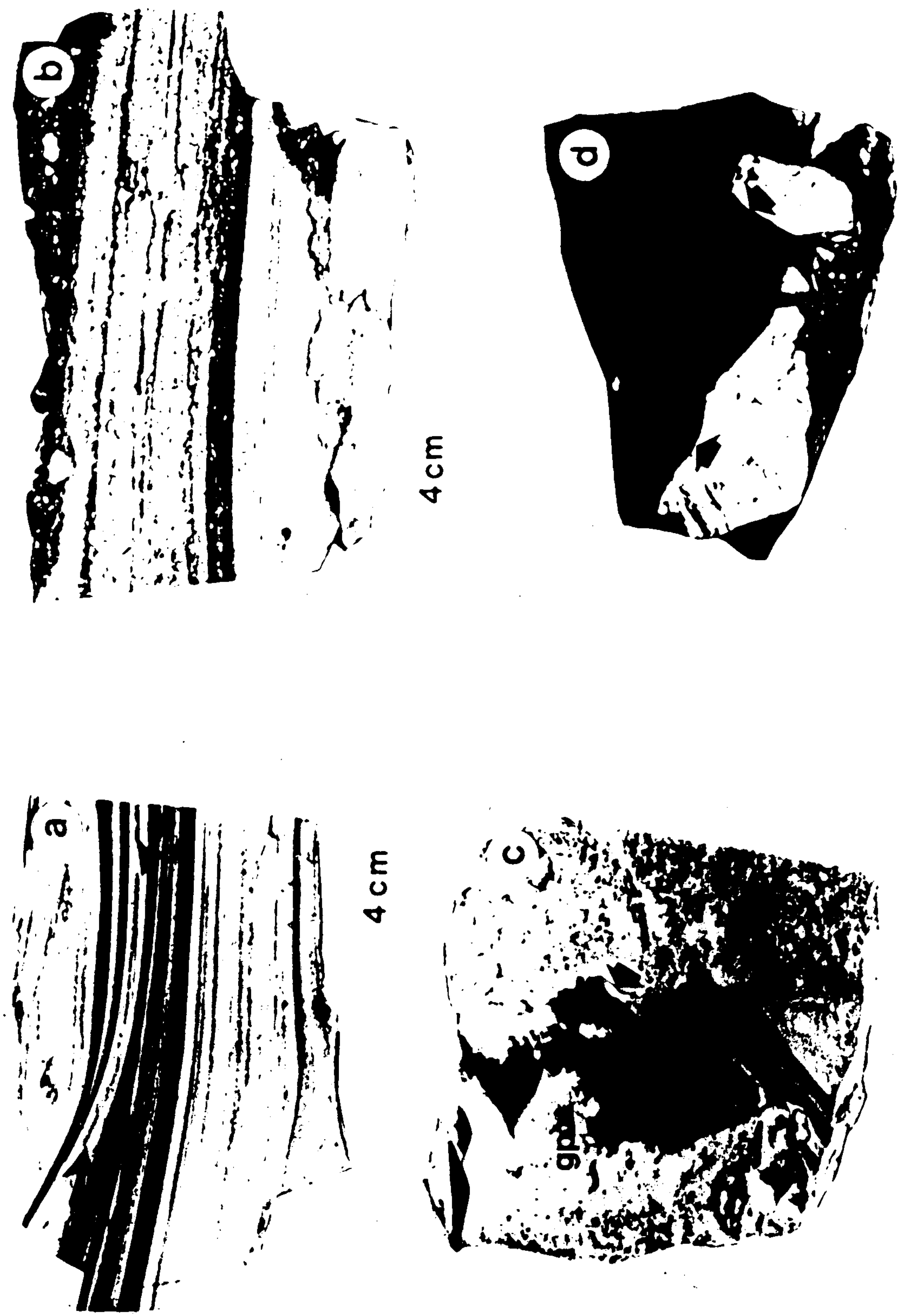

a
4 cm
b
4 cm
c
gp
4 cm
d
4 cm

Figure 12

Figures 12a & b: Slab faces of caymanite from the east end of the island, showing complex array of laminae, geopetal laminae, channels, and varying grain sizes. Channels formed in and were filled with caymanite, and later erosion carved another channel which remained partially void. Sample from Great Bluff, Locality 8 (Fig. 3). Oldest generation is #1.

Figures 12c & d: Slab faces of caymanite from Pedro's Castle Quarry. Three generations, separated by two channels are apparent, yet black channel-filling laminae (Fig. 12c) are not present on opposite face. Colour changes gradually between adjacent laminae.

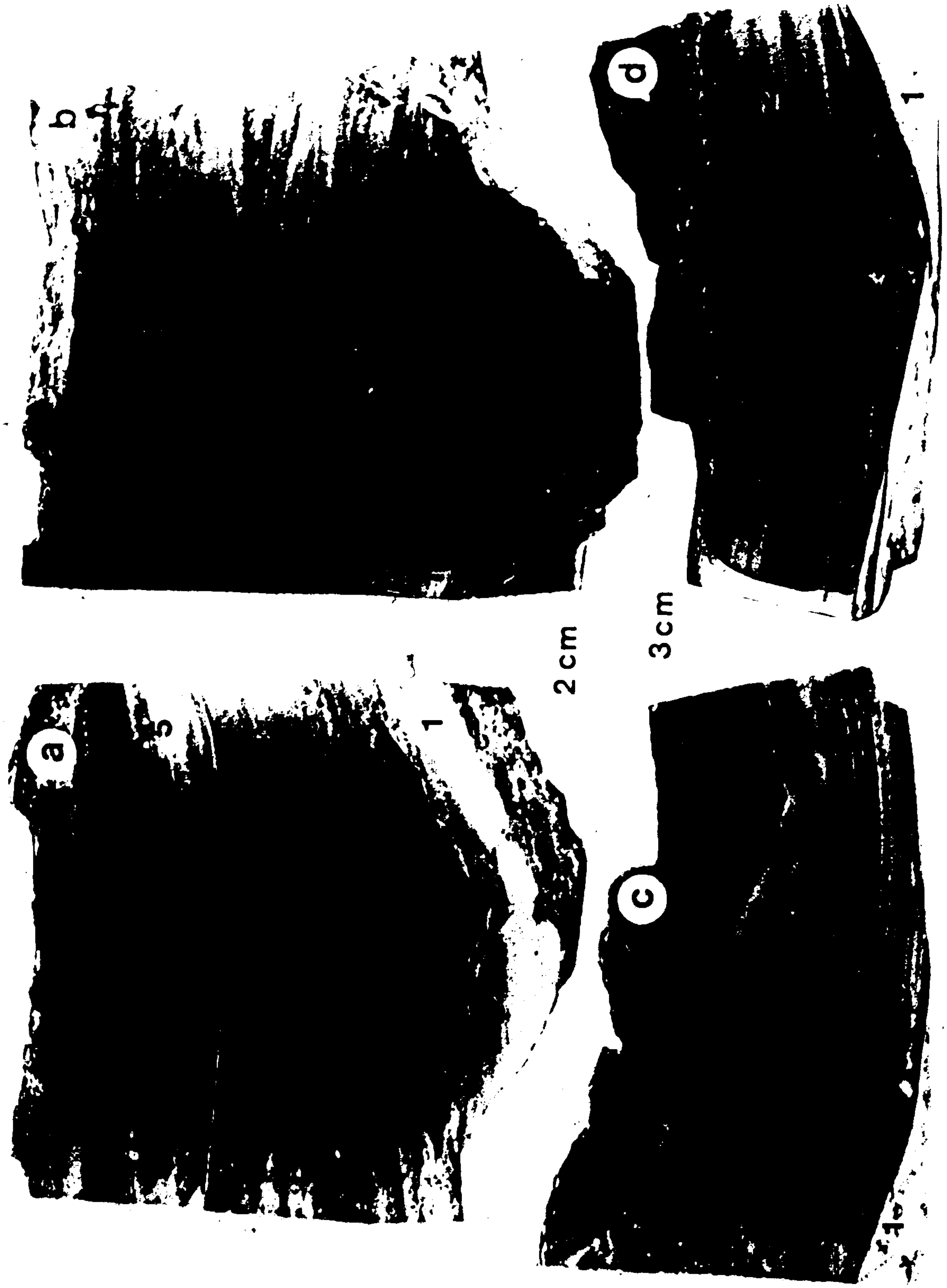

a
b
c
d
2 cm
3 cm

Figure 13

Negative photographic prints of thin sections showing attitudes of constituent laminae in the caymanite that is filling cavities that were created by the leaching of corals. Arrows indicate way-up. Tortuga Club, Locality 7 (Fig. 3). The scratches evident on the photographs are from the original thin sections. v=void.

a
b
1 cm

Figure 14

Figures 14a & b: Examples of manganese star dendrites (a) and manganese tree dendrites (b) developed on white and beige laminae in caymanite from East End, Locality 5 (Fig. 3). Figure 14b by Q. Goodbody.

Figures 14c,d & e: Examples of breccias which are commonly associated with the basal laminae of some caymanite sequences or, less commonly, in which the clasts are distributed throughout the entire sequence (Fig. 14e). The white clasts, which are derived from the Bluff Formation, are commonly coated with manganese. Figure 14d by B. Jones.


a
2cm
b
d
0.5 m

laminae. Commonly the colours, which enhance the interlaminae relationships, are what most clearly identify laminae (Fig. 11a). Some laminae sequences (Fig. 11d), however, have gradual colour transitions, thus obscuring laminae boundaries.

Stratigraphically and geographically closely spaced caymanite sequences are common at many localities. Despite their proximity such sequences are notably different. For example, at Locality 8 (Fig. 3), an outcrop of 1 m^2 contains 15 discrete cavities, all partly filled with caymanite. No two sequences have the same order of laminae colour, laminae thicknesses or laminae attitudes (Fig. 6e).

F. DENDRITES

Manganese star dendrites (van Straaten 1978) occur in some of the caymanite laminae (Fig. 14a) from the East End, Collier's Bay, and Tortuga Club localities (Fig. 3). Typically the dendrites are 2 - 3 mm, longest axis, and rarely up to 1 cm, longest axis. These dendrites occur on any colour lamina, and may span more than one lamina. Bands of tree dendrites up to 5 cm wide (Fig. 14b) apparently originated along contacts between adjacent laminae, and grew into and on top of the surfaces of these laminae.

G. BRECCIAS

Breccias with clasts of dolostone from the Bluff Formation and a matrix of unlaminated caymanite occur in some cavities (Fig. 14c) at Pedro's Castle Quarry and Blowholes localities (Fig. 3), and those on the east and northeast parts of the island. The angular clasts are up to 5 cm, longest axis, and may be concentrated either in the basal part of a caymanite sequence or spread throughout the sequence. In some examples the matrix is formed of either black or orange caymanite, but in one example, from Great Bluff (Fig. 3), the matrix is formed of laminated, multicoloured caymanite (Fig. 14e). In a hand sample from Great Bluff (Fig. 3), white dolostone clasts are coated by black manganiferous material (Fig. 11d) and occur in orange, gradationally laminated caymanite. Black coated clasts of white dolostone were also noted in the field (Fig. 11d). The breccias occur only in solution cavities, none were found in fossil moulds.

III. IMPORTANT CAYMANITE LOCALITIES

A. PEDRO'S CASTLE QUARRY

In the west wall of Pedro's Castle Quarry, caymanite occurred in a cave that was 10 m long; up to 2 m high, and, where visible, up to 2 m deep (Figs. 9, 10). The cave was destroyed by dynamite blasting in late 1984 or early 1985. There were four types of rock filling the cave. In vertical sequence they were: (1) caymanite; (2) a coarse grained, friable, highly porous calcitic dolostone; (3) lithified and semilithified terra rossa; and (4) flowstone (Figs. 9, 10).

CAYMANITE

The caymanite was formed of subparallel, uniformly thin orange, black and white laminae in the southern part of the cave. The caymanite was 1 to 10 cm thick, whereas in the northern part of the cave, the caymanite was up to 0.5 m thick. There, it comprised variably oriented white and beige laminae. The morphology of this caymanite may reflect the topography of the cave during caymanite deposition. There are two possible interpretations of the origin of this caymanite: (1) that it represents one depositional event but two styles of deposition, which generated the thinly laminated, brightly coloured caymanite and the thickly laminated white and beige caymanite; or (2) that it represents two separate depositional events. The first interpretation suggests that while the two types were deposited by the same depositional event, perhaps the cave floor topography affected the development of laminae morphology. More difficult to explain by this interpretation are the colours of the laminae since cave floor topography is not likely to affect pigmentation of laminae. The second interpretation might easily have resulted in different colours and thicknesses of caymanite simply because of different characteristics of the depositional waters. Examination of the outcrop at Pedro's Castle Quarry, however, did not shed any light on the relationship between the two types of caymanite, thus the problem remains unresolved.

CALCITIC DOLOSTONE

This homogeneous unit of white to buff, poorly lithified, calcitic dolostone overlay Unit 1 and thinned northward (Figs. 9, 10). The entire unit was 2 m wide, and up to 1.5 m thick. The subparallel laminae, which were up to 2 cm thick, were convex upward. The grains of dolostone are rounded to well rounded, one millimetre across (longest axis), and almost spherical to rarely (5%) completely spherical. Some foraminifera and ostracod tests were present (10% of the grains). The porosity of Unit 2 varies from 10 to 20%.

TERRA ROSSA

Terra rossa is a reddish brown layer, formed of the insoluble residue from the dissolution of limestone and dolostone outcrops. On Grand Cayman Island, the terra rossa formed a continuous layer of lithified and semilithified rock that was up to 20 cm thick (Figs. 9, 10). At the south end of the cave, terra rossa is interlayered with flowstone (Fig. 10). In the middle part and north end of the cave it was a discrete, consolidated unit which separates the the flowstone from the underlying caymanite. Terra rossa also formed a thin coating on the roof of the cave.

FLOWSTONE

Flowstone is a crystalline carbonate which is precipitated in the vadose zone of caves and cavities. Coarsely crystalline flowstone had been precipitated over the entire sequence of cave fillings, except at the south end of the cave, where the grainstone apparently filled the cave to the roof. The flowstone is brown to yellow on a fresh surface, but terra rossa had superficially coloured it red.

ATTITUDE OF LAMINAE

The caymanite and the dolostone have high dip angles, which are interpreted to be original sedimentary features. First, the laminae in the caymanite dip at angles up to 35° to the SE (Fig. 9). Second, laminae in the dolostone dip up to 36° to the SW (Fig. 9). It must be emphasized, however, that the angle of dip is variable throughout both of these units. There is no evidence of post-lithification movement among the laminae which might have altered the positions of these laminae. Third, the overlying flowstone (Figs. 9, 10) is virtually horizontal, which also suggests there has been no structural deformation of the cave sediments.

The contacts between each of the laminae in the units, and between the units themselves were distinct. This suggests that the laminae were sufficiently lithified prior to deposition of the subsequent lamina that mixing between adjacent laminae, or deformation of one laminae by an adjacent one, did not occur. There is a marked change in particle size between the caymanite and the dolograinstone, which indicates a change in the competence of the depositional water. The high energy of the water which carried the coarse grains in the dolograinstone would have caused erosion of the underlying, previously deposited caymanite unless the caymanite were (semi)lithified. Hence, a period of nondeposition occurred prior to the formation of the dolograinstone. This period was long enough for the caymanite to become lithified to the degree that when the water carrying the particles of dolograinstone flowed over it, it remained intact.

Figure 15

Figure 15a: Phytokarst at Hell with little associated soil or vegetation. The tree indicated by the arrow is 3m tall, and is rooted directly into the dolostone. Photo by B. Jones.

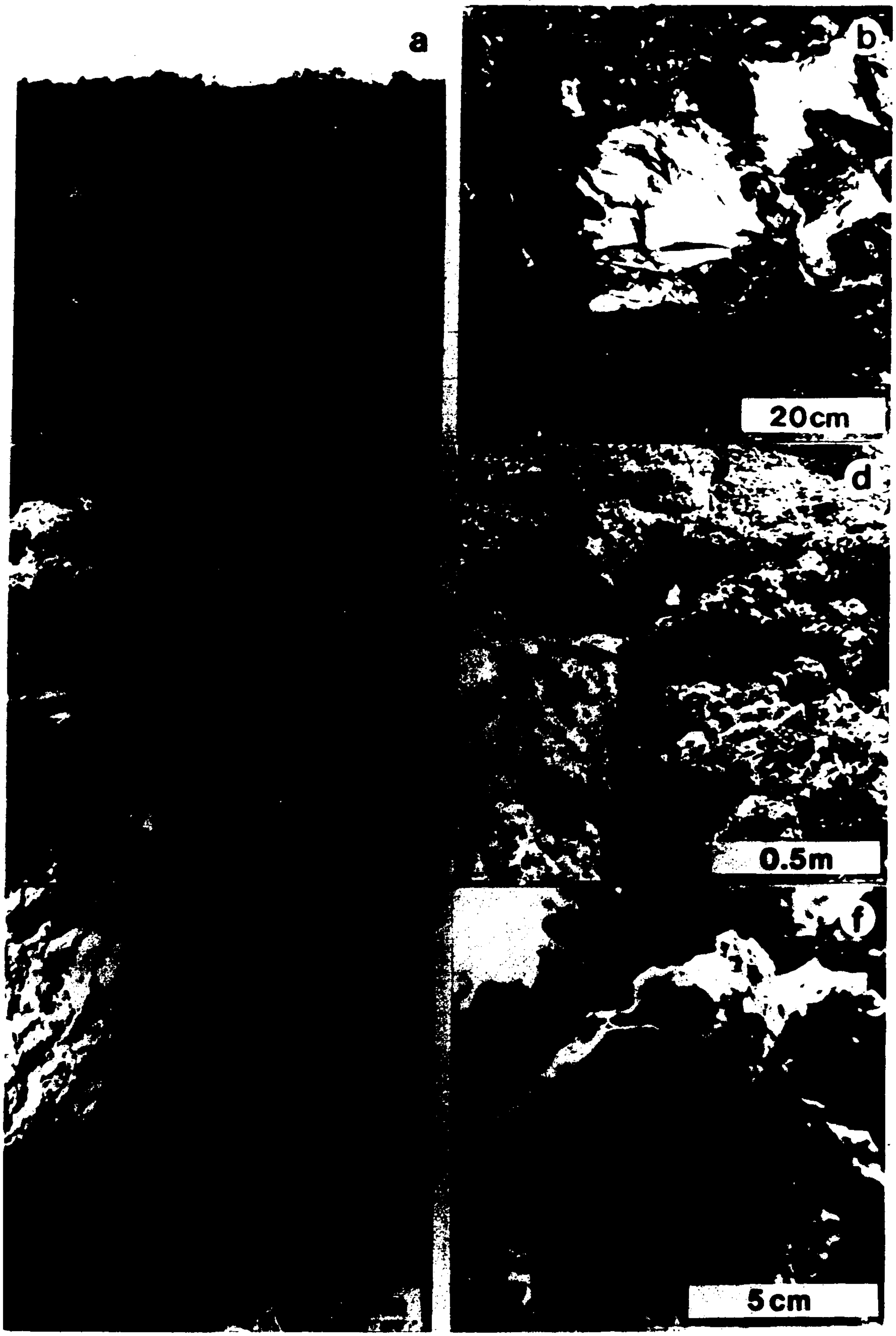
Figure 15b: Example of light coloured caymanite that is typical at Cayman Kai and Hell.

Figure 15c: Caymanite and interbedded red clay filling east dipping joint developed in the Bluff Formation at Blowholes. Photo by B. Jones.

Figure 15d: East-west trending vertical joint at Blowholes that is filled by flowstone and breccia. Caymanite has not been found in such joints. Photo by B. Jones.

Figure 15e: Example of caymanite from High Rock Quarry.

Figure 15f: Example of caymanite from Hell. Note the jagged and razor sharp edges associated with the weathered surfaces of the surrounding dolostone.


a
b
20cm
d
0.5m
f
5cm

B. CAYMAN KAI AND HELL

The caymanite at Cayman Kai is similar to that at Hell (Fig. 3). Caymanite at these localities is typically very light coloured (Figs. 15b and f): white being the predominant laminae colour; pink, grey, light orange and light beige are the other colours. Caymanite is more common in solution cavities than in those created by the leaching of fossils. There is a lack of terra rossa soil and vegetation on these outcrops (Fig. 15a), and a lack of red and orange coloured caymanite laminae. This is consistent with the typical association of terra rossa and vegetation with orange or red laminae, or conversely, the absence of all three components. Despite the present day associations, however, it is important to remember that the vegetation and/or soil patterns may have changed since the period when the caymanite was actually formed. Thus, there may not have been vegetation and soil covering an area where red or orange caymanite formed.

Unconsolidated sediment, which is accumulating in solution scallops in the Bluff Formation at Hell and Cayman Kai, and in joints in the Bluff Formation at Hell, resembles caymanite in five aspects:

1. The deposits are multicoloured, including black, brown, red and dark green. Caymanite is also distinctly multicoloured.
2. In scallops where the water has totally evaporated, dried clay sized sediment remains. Caymanite has a

similar, fine particle size.

3. The dried sediment in the solution scallops has a smooth upper surface, similar to the planar, smooth laminae surfaces of caymanite.
4. On a larger scale, both these sediments and caymanite occur in cavities created by solution, or in joint systems in the Bluff Formation.
5. No sediment was noted filling cavities created by the leaching of fossils at the Hell and Cayman Kai localities. Caymanite is also missing at these localities, however these may simply be two areas in which fossils were not present, and therefore not leached.

C. BLOWHOLES

The Bluff Formation at Blowholes (Fig. 3) has three distinct sets of joints. These joints as well as the fissures and cavities in the dolostone, have been enlarged by dissolution (Fig. 15d). Sheet-like bodies of caymanite, terra rossa, flowstone and breccias (Fig. 15c) fill some of the joints. Joint filling caymanite has not been noted elsewhere on the island.

D. HIGH ROCK QUARRY

Caymanite is rare in High Rock Quarry (Fig. 3). The caymanite that does occur is not as colourful as that elsewhere since black and grey laminae are absent. Manganese dendrites are also absent. Beige, buff, and light to medium orange are the predominant laminae colours. Both the number and sizes of occurrences are smaller than those on the east and northeast ends of the island. One sample, obtained from a boulder in this quarry contained a cavity filled with orange and beige caymanite and brownish orange terra rossa, the latter apparently cemented by brown calcite spar (Fig. 15e). The association of caymanite with another type of cavity fill, whether it is terra rossa, flowstone, or another type of rock, is rare. In this occurrence, however, subequal amounts of caymanite and terra rossa fill a cavity that is 15 cm across (longest axis). Caymanite at Pedro's Castle Quarry and Blowholes (Fig. 3) is associated with flowstone and other cavity fill material, but these are stratigraphically positioned and joint controlled caves. This could indicate that only these types of caves had an environment suitable for deposition of material other than caymanite, and that the randomly positioned cavities rarely did.

IV. COMPOSITION OF CAYMANITE

Six samples of caymanite were analysed by atomic adsorption (Table 1). The white laminae comprise chiefly calcium (32% in both samples) and magnesium oxides (20% in both samples), and have minor sodium (average 0.07%), iron (average 0.02%), and aluminium oxides (average 0.02%). There were also trace amounts of nickel, copper, and potassium. In one of the two samples (GC 83 W1), a small amount of manganese (<0.01%) was detected.

The orange laminae are formed of calcium (33%), and magnesium oxides (18%), iron (0.5%), aluminium (0.3%), manganese (0.1%), sodium (0.07%), and potassium oxides (0.1%), titanium (0.01%) and nickel (<0.01%).

The black caymanite, like the white and orange caymanite, is formed mainly of calcium and magnesium (average 32% Ca and 18% Mg). Characteristic of the black laminae is the manganese (3%), along with iron (0.25%), sodium (0.07%), aluminium (0.2%), minor nickel (0.08%), potassium (0.05%), phosphorus (0.04%), and copper (trace).

The almost exclusive occurrence of manganese in black caymanite and the similar confinement of iron to the orange lamina suggests that these oxides are responsible for pigmenting the laminae black and red, respectively.

A. COMPOSITION OF TERRA ROSSA

One terra rossa sample from Pedro's Castle Quarry (Figs. 3, 10) was analysed by atomic adsorption (Table 1). Aluminium is the most abundant component (27.7%); iron (12.8%), calcium (4.7%), and magnesium (2%) are also present. Manganese constitutes 0.25% of the sample.

B. MANGANESE CONTENT OF THE BLUFF FORMATION

The dolostone of the Bluff Formation contained 0.003% manganese oxide (Table 1), which, compared with the 3% MnO in black caymanite (Table 1), suggests that the source of the manganese in caymanite was not the Bluff Formation. It is possible, however, that the higher concentration of MnO in the black caymanite represents intense concentration from the Bluff Formation. This would necessitate one thousand-fold concentration of the dolostone to generate the levels of manganese noted in black caymanite. This leaves the ultimate source of the manganese in black and grey caymanite, and even the red and orange caymanite, undetermined.

C. PETROGRAPHY

Caymanite was examined with the SEM and binocular microscopes. Microcrystalline and cryptocrystalline anhedral and subhedral dolomite form 80% of the caymanite. Cloudy, structureless, peloidal material comprises approximately 8% of caymanite. Opaque manganese and iron rich minerals, which

Table 1. Chemical analyses of red, black, and white caymanite samples.

CONSTITUENTS	SAMPLE						
	GC 83 B1	GC 83 W1	GC 83 100	GC 83 453	GC 83 464	GC 83 466	GC 83 444
L.O.I.	45.87%	47.55%	46.72%	47.50%	45.79%	46.55%	
CaO	31.15	32.39	32.66	31.93	33.14	33.75	4.67%
MgO	18.60	19.81	18.62	20.37	17.44	17.99	2.02
MnO	3.11	< 0.01	0.06		2.99	0.13	0.25
Fe_2O_3	0.29	< 0.01	1.43	0.03	0.20	0.54	12.84
Na_2O	0.08	0.08	0.05	0.06	0.05	0.10	
K_2O	0.02	< 0.01	< 0.01	< 0.01	0.07	0.09	
NiO	0.10	Tr	Tr	Tr	0.06	< 0.01	
Al_2O_3	0.34	< 0.01	0.13	0.03	< 0.01	0.38	27.70
P_2O_5	0.05				0.03		
CuO	0.01	< 0.001	< 0.001	Tr	< 0.01		
TiO_2						0.01	
	99.62	99.83	99.67	99.92	99.77	99.53	
CO_2%	43.13	46.83	46.24	46.50	44.59	45.55	

are amorphous in thin section and are spheroidal or encrusting under the SEM, occur abundantly in black, grey, and less commonly in the orange and red caymanite laminae. This opaque matter can constitute large amounts of caymanite laminae, or can be nonexistent as in the white laminae. Euhedral dolomite, which is distinct in both thin section and the SEM, forms approximately 5% of caymanite.

Whereas red, black, and white laminae are vivid in hand specimen, in thin section (transmitted light) the colours are dull (Fig. 16e). White laminae are dull grey to white; orange and red laminae are also dull grey but can be brownish; and black and grey laminae are dull grey to opaque.

ANHEDRAL AND SUBHEDRAL DOLOMITE

This is the most common dolomite morphology (Figs. 17a and c). The crystals vary from less than 1μ to 10μ, and rarely up to 30μ, longest axis (Fig. 17e). The crystals typically are interlocking and rounded or abraded. There is both primary abrasion (Fig. 17a) and evidence of dissolution (Fig. 18a). This is true for all of the caymanite laminae, irrespective of colour. Some of the subhedral crystals show smooth cleavage planes or a step-like pattern (Fig. 18c).

PELOIDS

The peloids in caymanite are light to medium grey in white and grey laminae; reddish brown in orange and red

Figure 16

Figures 16a & b: Photomicrographs of dolomitized red algae fragment (a) and foram (b). Examples such as these are rare.
Figure 16c: Cavity filled with caymanite and spar calcite.
Figure 16d: Examples of opaque manganese and ironrich biogenic structures in caymanite (arrows).
Figures 16e & f: Relationship between caymanite and cavity walls. In both examples the walls of the cavity were lined by precipitated dolomite crystals prior to deposition of the caymanite. Figures 16 a - f from Tortuga Club, Locality 7 (Fig. 3).

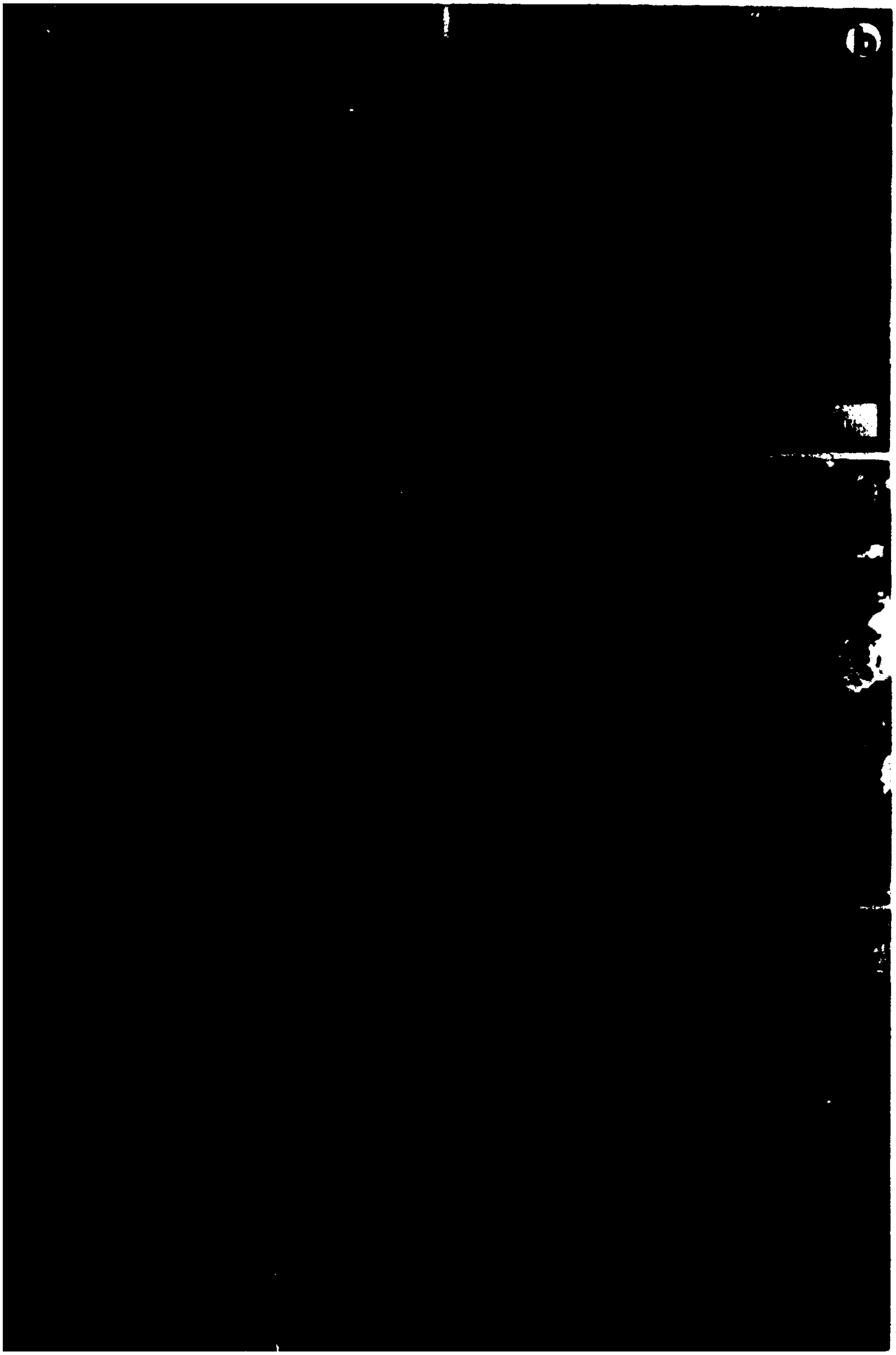


Figure 17

SEM photomicrographs.
Figure 17a: Anhedral dolomite which forms the groundmass of most caymanite.
Figure 17b: Euhedral dolomite crystals lining cavity wall in caymanite.
Figure 17c: Distinctly cleaved anhedral dolomite.
Figure 17d: Example of manganese and iron rich spheroid (bacteria?) in a ground mass of euhedral dolomite crystals.
Figure 17e: Dolomite matrix characteristic of caymanite.
Figure 17f: Calcite, rare in caymanite, with pronounced cleavage.

Figures 17 a & f from Great Bluff, Locality 8; Figures 17 b, c, d, & e from Tortuga Club, Locality 7 (Fig. 3).

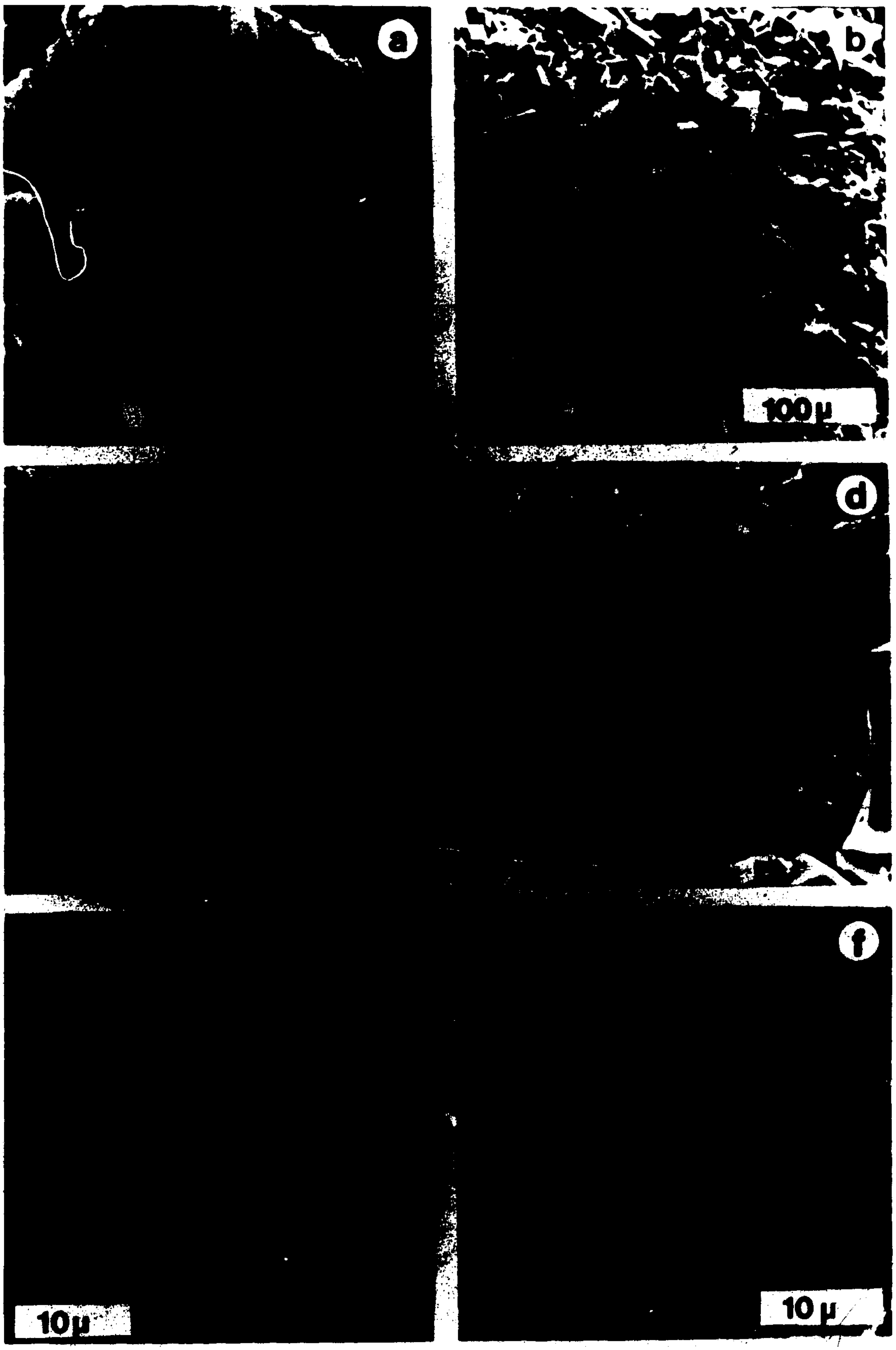
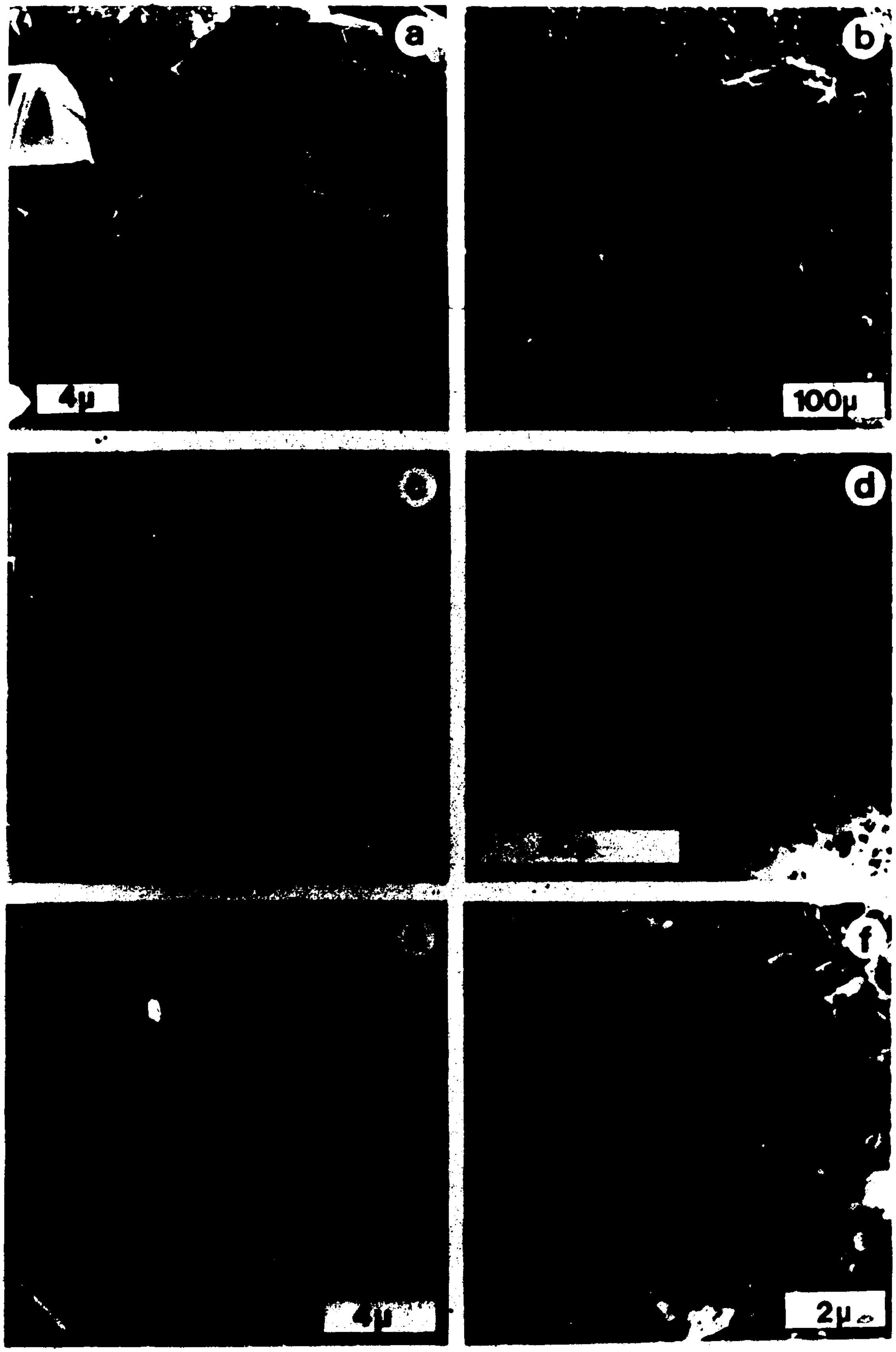

a
b
100µ
d
f
10µ
10µ

Figure 18

SEM photomicrographs.
Figure 18a: Etched dolomite crystals.
Figure 18b: Calcite crystals lining a pore that occurs in orange caymanite.
Figure 18c: Etched dolomite crystal showing cleavage.
Figure 18d: Whisker calcite crystals in a pore developed in orange caymanite.
Figure 18e: Partly leached dolomite crystals.
Figure 18f: Euhedral dolomite crystals lining a pore in (white) caymanite.

Figures 18d and f from Great Bluff, Locality 8; Figures 18 a, b, c, & e from Tortuga Club, Locality 7 (Fig. 3).


a
4μ
b
100μ
d
f
2μ

laminae; and not visible in black laminae (because of opaque amorphous black material). The peloids are cryptocrystalline dolomite, 50 - 100μ in diameter and some (less than half) have a 10μ thick rim of clear microcrystalline dolomite. The peloids are cemented with dolomite. Samples were also noted with peloids at such a high density that only their internal characteristics suggested they were peloids: the rounded shape was not visible, and microcrystalline dolomite cement occurred only in vugs.

EUHEDRAL DOLOMITE CRYSTALS

Limpid (in the sense of Folk and Siedlecka 1974; and Folk and Land 1975) euhedral dolomite crystals, constitute 5% of caymanite, and occur in all laminae examined. The average size of these rhombohedra is 10μ, longest axis, but extremes of 2 to 30μ, longest axis, occur. The limpid dolomite occurs in three settings:

1. as linings of minute pores (15 to 20μ, longest axis) in caymanite (Fig. 18f). These pores are probably younger than the host caymanite because euhedral dolomite, which lines these pore walls, is rare, and thus not syngenetic with caymanite.
2. as a cement along the walls of the cavities in which the caymanite was deposited. In thin section these clear crystals are easily identified along the cavity walls (Fig. 16f) because of their large size and clarity against the fine grained caymanite matrix. On the SEM

the crystals of euhedral dolomite are contrasted sharply with the anhedral and subhedral dolomite of the caymanite (Fig. 17b).

3. as isolated rhombs surrounded by caymanite. These crystals, up to 12μ, longest axis, are associated with manganese and iron rich spheroids (Fig. 17d).

Solution phenomena are evident on cleavage faces of some dolomite crystals (Figs. 18a and c). Despite the dissolution the crystals have maintained their euhedral morphology. Another type of dissolution on the dolomite rhombs is the actual removal by solution of the interior of dolomite crystals (Fig. 18e). The consequent void in the centre of the crystal is also rhombohedral, and duplicates the morphology of the host crystal. Dissolution apparently occurred along cleavage planes of the dolomite crystal. Similar crystals of dolomite with hollow zones were illustrated in thin section by Ward and Halley (1985, p. 411). They also interpreted these to be the result of dissolution of zones of higher solubilities.

CALCITE

Although there is no authigenic calcite in caymanite, there is both subequant (Fig. 18b) and acicular, whisker (Scholle 1978) calcite lining secondary vugs in the laminae (Fig. 18d). The polyhedra are up to 100μ, longest axis; and the whisker crystals are 1 to 2μ wide and up to 20μ long. Calcite also occurs as large anhedral particles (up to 50μ, longest axis) in the matrix of caymanite (Fig. 17f). Calcite spar has commonly filled voids in cavities with geopetal caymanite (Fig. 16c).

OTHER MINERALS

Minor non-carbonate material occurs in white and red caymanite: in GC 83 460, two grains rich in Al and Ca were noted (Fig. 19d); and in GC 83 462, rod shaped, iron rich non-carbonate and non-organic minerals were noted (Fig. 22c).

Aluminium and silica rich particles are noted in black and grey caymanite, such as in GC 83 100 (Fig. 19f) which also is enriched in Fe and Ca. A spherical grain, rich in K and Si was noted in GC 83 431 (Fig. 19e). A spheroid rich in Mn, Fe, Si, and K was noted in GC 83 100 (Fig. 19c). The spheroid, with a platy surface texture, does not look organic because of its apparent lack of bulbous structure (J. Campbell, University of Alberta, pers. comm. 1985). It is possible, however, that this is a mineralized bacterial colony, and that the surface texture is a function of the mineral precipitate rather than an underlying colonial structure.

POROSITY

Vuggy and intercrystalline porosity in caymanite is distinct in thin sections made of samples which have been impregnated with blue epoxy, although it is not photogenic.

Figure 19

SEM photomicrographs of spheroids that are probably mineralized bacteria.

Figure 19a: Manganese rich spheroid.

Figure 19b: Pore in dolomite of caymanite with a manganese-rich area (white arrow) and manganese-rich bacterial filaments (black arrow).

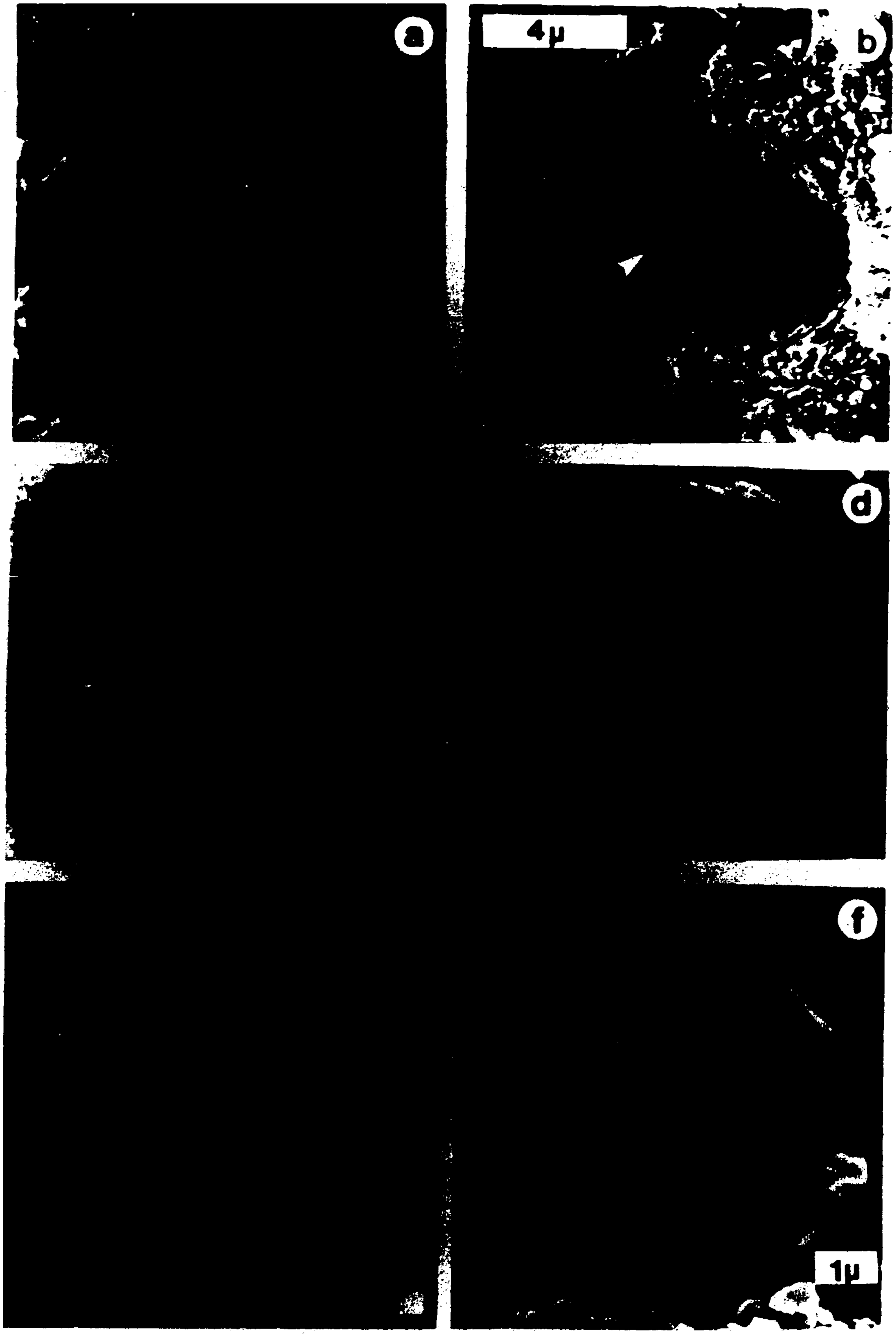
Figure 19c: Spheroid from black caymanite, rich in Mn, Fe, Si, and K. Platy mineral precipitate has probably coated a bacterial colony and disguised the bulbous surface texture.

Figure 19d: Grain from white caymanite, non-carbonate, rich in Al and Ca.

Figure 19e: Spheroid from grey caymanite, non-carbonate, rich in Si and K

Figure 19f: Al and Si rich grain from black caymanite.

Figure 19d from Great Bluff, Locality 8; Figs. 19a, b, c, e, & f from Tortuga Club, Locality 7 (Fig. 3).


a
4μ
b
d
f
1μ

Commonly the porosity type and amount change from one lamina to the adjacent ones. Vuggy porosity is rarely higher than 5%; and intercrystalline porosity is rarely greater than 2%. The secondary, or vuggy pores commonly have limpid dolomite (Fig. 18f; Figs. from Jones *et al*. 1984), calcite spar (Fig. 18b), or whisker calcite (Fig. 18d) precipitated along the pore walls. The permeabililty of caymanite is low.

FOSSILS

Fossil fragments, up to 0.5 mm long, occur rarely in caymanite. Ostracods are the most abundant fossil, but foraminifera (Fig. 16b) and gastropods also occur. Red algae were found in laminae of coarse dolograinstone, which alternate with laminae of caymanite (Fig. 16a).

V. PIGMENTATION OF CAYMANITE

A. DISTRIBUTION OF MANGANESE

Chemical analyses of caymanite laminae indicate that black laminae contain up to 3% Mn, 1.43% Fe, 0.1% Ni, and 0.1% Cu (Table 1). Such analyses, however, do not show whether these elements are located in the dolomite lattice, or in separate, discrete bodies. The EDX analyser attached to the SEM is useful in this regard, since individual crystals and grains can be analysed. No metallic impurities, such as Mn, Fe, Ni, or Cu were detected in the euhedral and anhedral dolomite crystals (Fig. 20e). In thin section, opaque, amorphous minerals occur in all but the white laminae (Fig. 16d). With the EDX analyser manganese or iron are noted in all but the white caymanite (Fig. 20). These opaque minerals are believed to be the same manganese and iron rich phenomena noted in SEM caymanite samples. In thin section they are patches of black, dark brown or dark red material, up to 50μ, longest axis.

SPHEROIDS

Scattered throughout the black and red caymanite are well defined spherical bodies, rods and more rarely aluminium rich particles. The spheroids are 2μ (Fig. 21c) to 17μ (Fig. 21a) in diameter. They are almost perfectly spheroidal, except for one (Fig. 21e), which is ovate. Four surface textures occur:

Figure 20

EDX analyses of:

Figure 20a: Dolomite in white caymanite
Figure 20b: Orange caymanite
Figure 20c: Type 1 spheroid, framboid surface texture (see Fig. 21d)
Figure 20d: Type 3 spheroid, smooth surface texture (see Fig. 21c)
Figure 20e: Dolomite crystal in black caymanite laminae
Figure 20f: Types 2 and 4, rubbly and knobby surface textures (see Figs. 21b and e) have similar compositions.

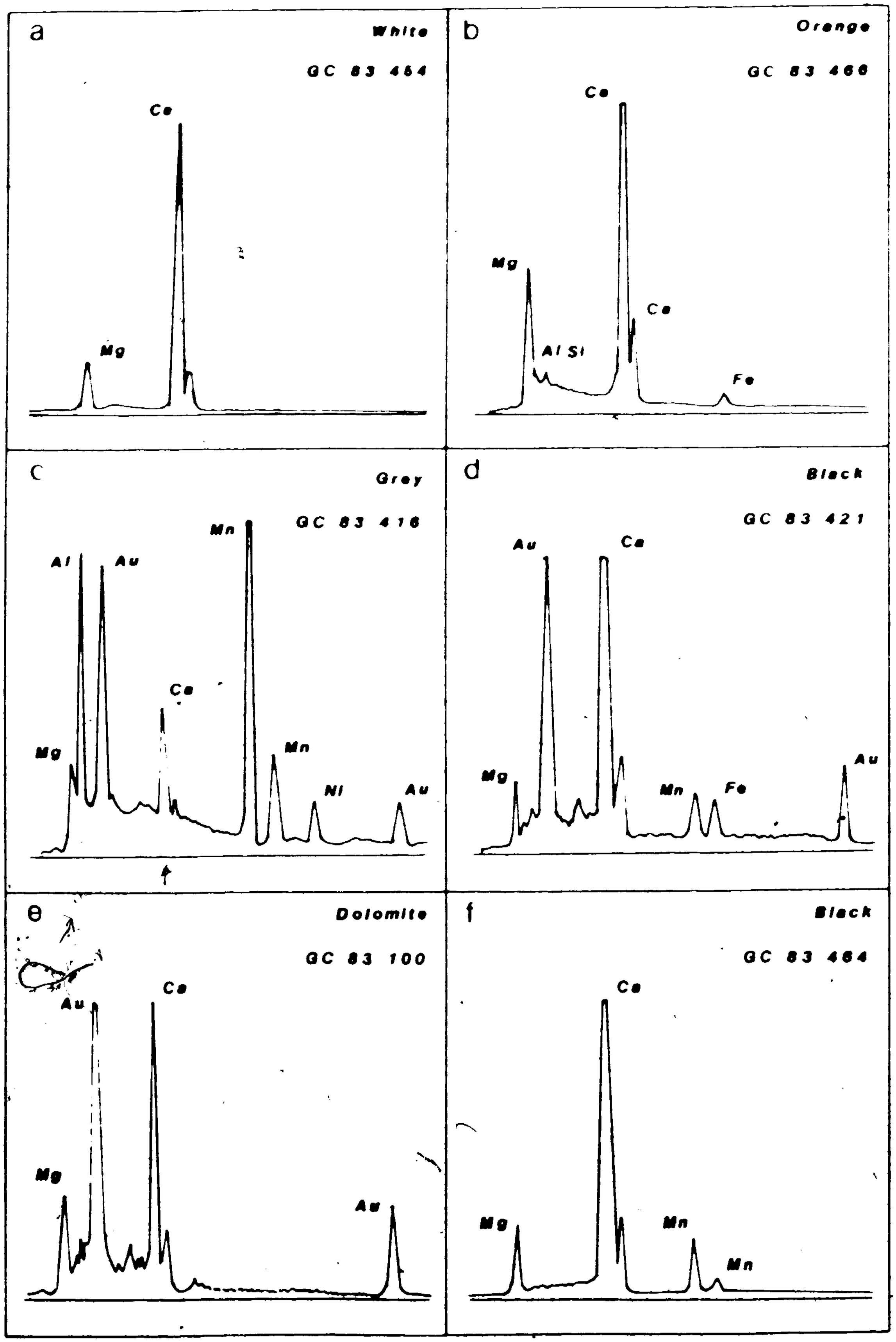

a
White
GC 83 464
Ca
Mg
b
Orange
GC 83 466
Ca
Mg
Al Si
Ca
Fe
c
Grey
GC 83 416
Mn
Al
Au
Ca
Mg
Mn
Ni
Au
d
Black
GC 83 421
Au
Ca
Mg
Mn
Fe
Au
e
Dolomite
GC 83 100
Au
Ca
Mg
Au
f
Black
GC 83 464
Ca
Mg
Mn
Mn

Figure 21

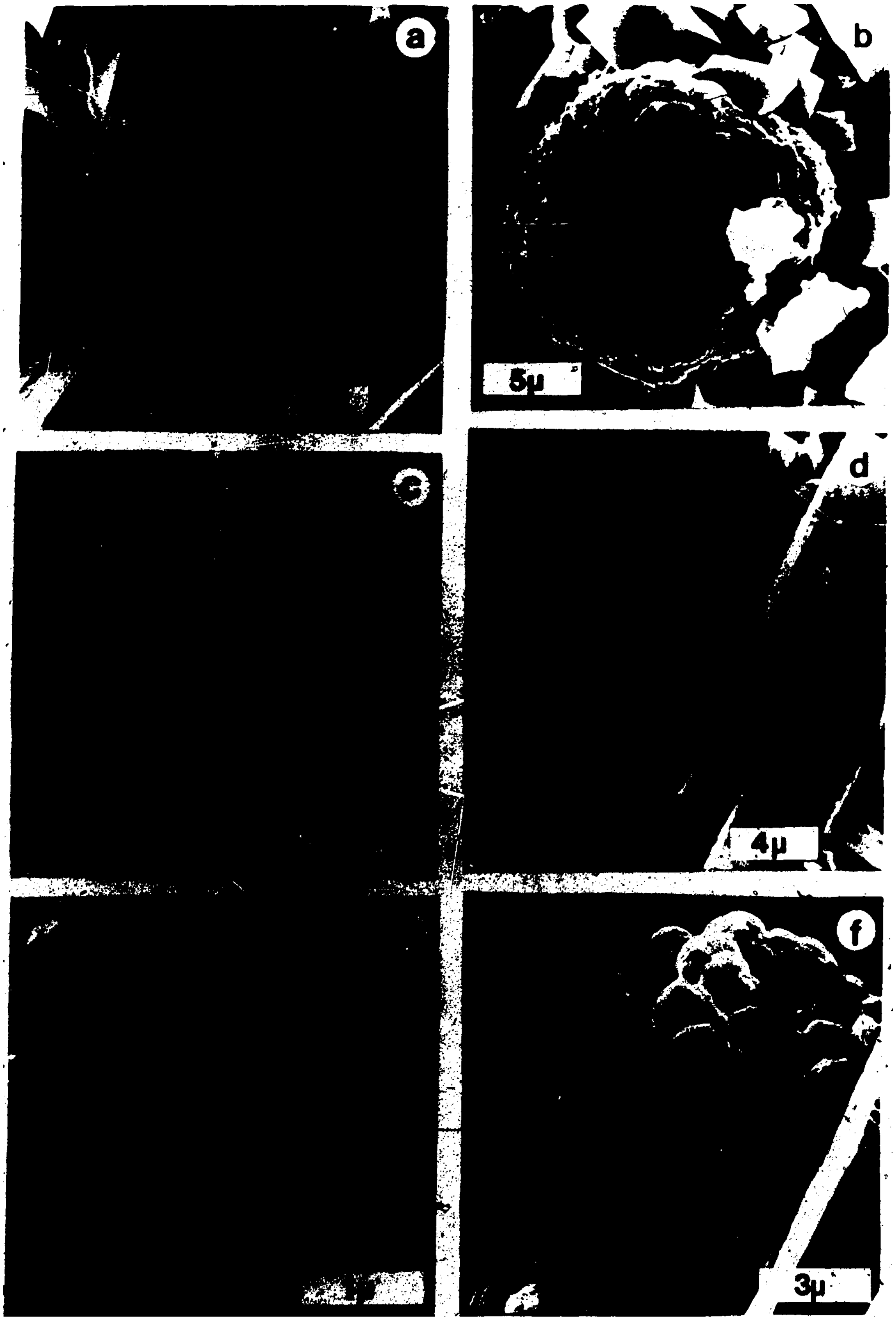
SEM photomicrographs of metalliferous spheroids set in the dolomitic ground mass of the caymanite. Such spheroids are probably bacteria.

Figure 21a & b: Type 2 spheroids that are coated by manganese (a) or manganese with some nickel (b).

Figure 21c: Type 3 spheroid that is coated with manganese and iron. This type is significantly smaller than Type 2 illustrated in Figures 21a and 21b.

Figure 21d & f: Type 1 spheroid that is coated with manganese, aluminium and nickel. (f) is an enlarged view of (d).

Figure 21e: Type 4 spheroid that is coated with manganese. All samples from Tortuga Club, Locality 7 (Fig. 3).


a
b
5μ
d
4μ
f
3μ

1. *FRAMBOID* (Figs. 21d and f); these spheroids consist of hundreds of minute balls, each approximately 1.5μ in diameter. Spheroids of this type are 15 to 17μ in diameter. Each of these balls appears to be made of angular plates, that are less than 1μ thick (Fig. 21f).
2. *RUBBLY* (Figs. 21a and b) this texture resembles a framboid structure in so far as it is formed of hundreds of particles less than 1μ, longest axis. Unlike a framboid texture, however, these particles are not distinct and appear to have grown together or have been coated by material, thus obscuring the individual grains. These spheroids are 15 to 17μ in diameter.
3. *SMOOTH* (Fig. 21c) these are up to 2μ in diameter. These spheroids can occur in high densities; for example, 17 occur in a $64\mu^2$ area of one sample (Fig. 22a).
4. *KNOBBLY* (Fig. 21e) these ovate spheroids, up to 2μ in diameter, are characterized by 0.2μ (diameter), radiating projections.

CRUSTS

In some samples crusts of manganese-rich spheroids and rods coat the dolomite grains (Fig. 22b). Some of these crusts apparently caused corrosion of adjacent dolomite particles (Fig. 22b). Close examination of these coatings shows that they are composed of masses of tiny (less than 1μm, longest axis) spheroids and short stubby rods (Figs. 22a and d). There may be a genetic link between the

Figure 22

SEM photomicrographs.

Figure 22a: Crust of manganese-rich spheroids (arrows) and filaments coating dolomite crystals in caymanite.

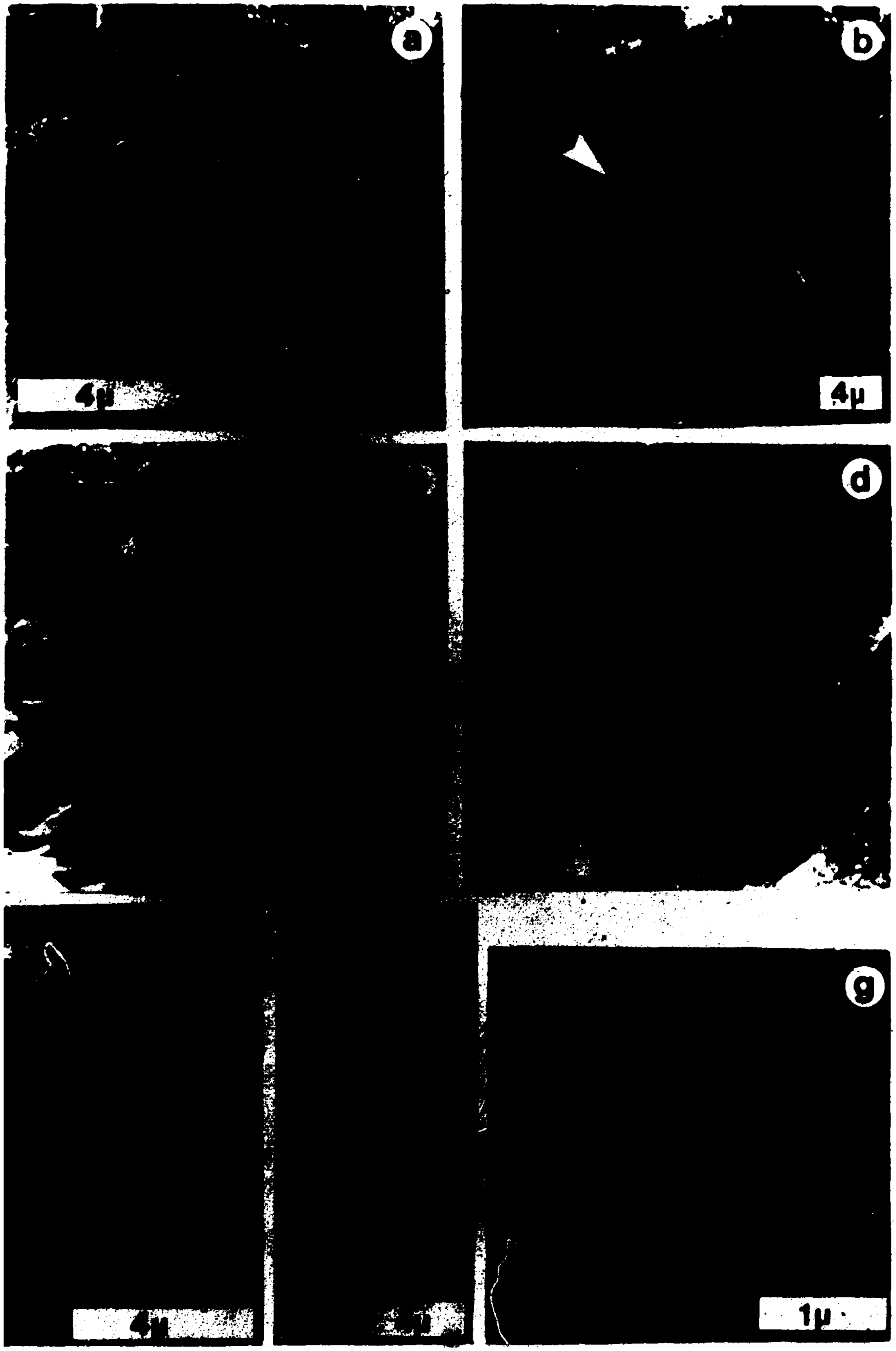
Figure 22b: Dolomite crystals apparently corroded and replaced by manganese (arrow).

Figure 22c: Bacterial(?) rods in red caymanite. The filaments are too thin to be analysed using the EDX analyser.

Figure 22d: Crust of manganese coating dolomite crystals in caymanite. The circular structure in the center of the photograph marks the place where a spheroid was once located.

Figures 22e, f & g: Examples of bacterial(?) filaments (arrows) present in caymanite. The filaments in (e) and (f) are too thin to be analysed by the EDX analyser. The clusters of filaments in (g) are coated with iron.

Figures 22b, c, & d are from Great Bluff, Locality 8; Figures 22a, e, f, & g are from Tortuga Club, Locality 7 (Fig. 3).


a
4μ
b
4μ
d
g
1μ

constituents in the crusts and those in the spheroids and rods, because all involve concentration of manganese.

FILAMENTS

There are two types of rods in the black and grey caymanite, namely (1) separate strings less than 1μ wide but at least 2μ long (Fig. 22e), rare ones are spiraled (Fig. 22f); and (2) aggregates of short rods, each rod measures less than 1μ wide and long (Fig. 22g). The second type occurs both as distinct three dimensional accumulations (Fig. 22g) and as coatings on top of the predominantly dolomite groundmass (Fig. 22b).

B. COMPOSITION OF SPHEROIDS, CRUSTS AND FILAMENTS

Each observed spheroid was analysed using the EDX analyser on the SEM. Type 1 spheroids contain manganese, aluminium, and nickel (Fig. 20c), nickel, whereas Type 2 spheroids contain only manganese (Fig. 20f). In Type 3 spheroids iron and manganese are present (Fig. 20d), while in Type 4 spheroids only manganese was detected (Fig. 20f). Calcium and magnesium were not detected in any of the spheroids.

EDX analyses of the crusts coating the dolomite rhombs demonstrate that these are rich in manganese. No iron or nickel was detected.

The mineralogy of the rods, where they occur individually is difficult to determine because they are so small. Since the beam diameter on the EDX analyser is typically larger than the rod width, it is difficult to obtain an accurate analysis. The aggregates of short rods (Fig. 22d) were found, however, to be rich in manganese. A grey lamina contained one iron rich, manganese deficient accumulation of short rods (Fig. 22g).

C. ORIGIN OF STRUCTURES

Extensive discussion with L. Sigler (1985, Curator, Mould Herbarium, University of Alberta), J. Campbell (1985, Department of Microbiology, University of Alberta), and S. Pirozynski (1985, Museum of Man and Nature, Ottawa) suggested that these structures resembled organic rather than inorganic material. The possibility of fungal origin was eliminated because: (1) these structures are smaller than those usually associated with fungi (Campbell 1985, pers. comm.) and (2) fungi do not usually derive their nutritional requirements from the oxidation of minerals (Campbell 1985, pers. comm.; Sigler 1985, pers. comm.).

Other reasons why the spheroids, rods and crusts in the black and grey caymanite are believed to be of organic origin include:

1. The branching of these rods, and the breaking along certain points (or formation of septal walls) are two characteristics of microorganisms (J. Campbell 1985, Dept. of Microbiology University of Alberta, pers. comm.).

2. Similar morphologies were noted to have common diameters: for example Type 1 spheroids (Fig. 21a) were noted to have diameters between 15 and 17μ.
3. Chemical analyses of caymanite samples show that the minerals required by microorganisms (Brock *et al.* 1984) are present in caymanite. Phosphorus, potassium, magnesium, calcium, and sodium are nutrients required in relatively large amounts. Manganese and copper are nutrients commonly required in relatively small amounts by microorganisms. Iron is necessary in intermediate amounts. These eight elements are present in caymanite, although phosphorus is only in two of the six samples. While more than these eight elements are required to create a suitable environment for microbiota, their presence is positive support.
4. The Types 3 and 4 spheroids yielded very low EDX responses, which, according to G. Braybrook (SEM technician, University of Alberta; pers. comm. 1985), indicates a biogenic composition.
5. The structures, especially the filaments, occur both singly and in clusters (Figs. 22d and g). Kazmierczak (1979) used this criterion of spatial distribution to establish biogenicity. This is based on comparison with Devonian microspheres of established biogenicity, which occur as isolated bodies and in clusters (Kazmierczak 1979).
6. There are similarities between the caymanite microbiota

and those reported in the literature. These include: a) Kazmierczak's (1979, p. 4) observation that laminations in Precambrian cherts in the Gunflint Iron Formation in Canada are "emphasized by abrupt changes in spatial density of the microspheres...". This compares with caymanite because the caymanite laminae are characterized by colour, which in turn is caused by manganese and iron believed to be concentrated by bacteria. b) Most of the spheroids and filaments were noted in black and grey caymanite. Although an explanation of why they were found only in these and not in orange and red laminae (and yet, are extrapolated to occur there), is necessary, it is interesting to read of similar observations by Awramik and Barghoorn (1977) and Knoll and Barghoorn (1976). The first pair found microfossils in the black and bluegrey chert laminae. Their comment (Awramik and Barghoorn 1977, p. 129) "... preservation in rocks other than dark grey to black cherts is poor,..." and classification of such poorly preserved material is unusually subjective and fraught with complications resulting from degradation", is reminiscent of the good preservation of structures in black and grey caymanite and apparent lack of preservation of structures in orange and red caymanite. The second pair found microfossils in black chert laminae in a host dolomite and not in the accompanying red laminae, a similar observation to caymanite.

7. The microstructures found in caymanite are believed to have been deposited, regardless of their biologic or abiotic origin, in a cave environment. Thus, the morphology of these structures, if biogenic, should be similar to extant microorganisms (Awramik and Barghoorn 1977) living in caves.

8. The spheroids bear no resemblance to known minerals rich in manganese, iron, or nickel. The only exception noted is a spheroid from black caymanite (Fig. 19c) rich in Mn, Fe, Si, and K. It resembles inorganically precipitated birnessite (rich in Mn, and Na or Ca) illustrated by Sorem and Fewkes (1977, p. 159).

Concrete proof of biogenicity of these spheroids and filaments would be evidence of cell structures. Biogenicity could also be supported, although not proven, by statistical analyses on distribution and diameters of the structures. The number of structures photographed are inadequate for statistical analyses, thus this will not be used to establish biogenicity. Second, the structures have commonly been permineralized and therefore are impossible to examine for internal cell structures. Furthermore, the scale of these structures (less than 20μ, longest axis), and the method of examination (SEM) complicate any sectioning of the structures to check for internal detail.

D. OCCURRENCES OF MANGANESE

The association of bacteria and manganese in cave deposits, such as caymanite, is common (Moore 1981; James and Choquette 1984). The composition of caymanite is similar to deep marine ferromanganese nodules because of their mutual association of bacteria with manganese and iron (-the latter association was noted by Sorem and Fewkes 1979; Dean and Ghosh 1980).

MANGANESE IN CAVE ENVIRONMENTS

Manganese is a common accessory mineral in cave environments (White 1962; Broughton 1971; Hill 1976). Manganese rich caymanite, which developed in caves and cavities, is similar in other respects to other manganese rich sediments. Black laminated manganese rich cave fillings, were observed by Broughton (1971). Black coatings on angular breccia clasts are noted on Grand Cayman Island at the bases of some caymanite sequences (Fig. 14c); similarly, pebbles coated by manganese rich minerals have been noted by White and Dunn (1962), Broughton (1971), Hill (1976), Potter and Rossman (1979), and Moore (1981) in cave streams. Hill (1976, p. 51) noted that cave associated manganese minerals are "... extremely fine grained and hard to identify even with X-ray techniques"; this is also true for caymanite.

Manganese in caves is most commonly associated with organisms (Moore and Nicholas 1964, Broughton 1971, Hill

1976, Laverty and Crabtree 1978, and Moore 1981). Broughton (1971) suggested that "... bacteria utilise the organic part of the complex molecules, thus freeing the manganese ions and causing the cave water to become supersaturated with manganese near the bacterial colonies". Moore (1981) noted that manganese in a cave in West Virginia, USA, might have come from leaves in a pond. Bacteria removed oxygen from manganous compounds in the leaves, yielding manganic compounds. James and Choquette (1984, p. 176) noted that "... the black, sooty coating on cave walls and pebbles is a variety of manganese minerals whose precipitation is aided by specialized bacteria".

MANGANESE IN NODULES

The chemistry and microbiology of black and red caymanite resemble those of marine and lacustrine ferromanganese nodules. For example, the metallic elements present in black caymanite and nodules (Cronan 1976; Calvert and Price 1977), in order of diminishing abundance, are manganese, iron, nickel, and copper (Table 1). Manganese and iron rich caymanite laminae have small amounts of iron and manganese, respectively (Table 1). Similarly, laminae in nodules also are rich in either manganese or iron, and have minor concentrations of the second element (Calvert and Price 1977; Sorem and Fewkes 1977). The red caymanite laminae contained only traces of nickel (Table 1) and less than trace amounts of copper (Table 1).

There are spheroids in caymanite which are organic, probably bacterial in origin, and Sorem and Fewkes (1977) described similar structures in the ferromanganese nodules from the seafloor. The amorphous manganese and iron hydroxides in the nodules have flocculated and coalesced "into larger botryoidal masses" (Sorem and Fewkes 1977, p. 160). There is no suggestion made by Sorem and Fewkes (1977) that these might be bacterial or even organic, but it is a possibility to be considered.

VI. ORIGIN OF CAYMANITE

A. CRITERIA OF THE DEPOSITIONAL MODEL

In determining the origin of caymanite, any model must fit the following observations:

1. The nonmarine diagenetic setting of the Bluff Formation before and after caymanite formed.
2. The predominance of anhedral (detrital) dolomite, and minor amounts of rhombohedral, limpid (primary) dolomite.
3. The high percentage of marine fossils in laminae of dolograinstone which alternate in sequence with caymanite laminae.
4. The apparent stratigraphic control to the filling of caves with caymanite, such as at Pedro's Castle Quarry, and East End.
5. The microorganisms (bacteria?) in the black and grey caymanite; and, by inference, in red and orange caymanite although none were noted with the SEM.
6. The presence of manganese, iron, and minute amounts of nickel and copper in black, grey, red and orange caymanite.
7. The multiphase depositional system which deposited the laminae.
8. The features such as channels, which indicate high water velocity, cut into caymanite laminae, which represent lower water velocity. In turn, the channels were filled

with caymanite laminae, again representing lower water velocities.

B. OCCURRENCES SIMILAR TO CAYMANITE

Caymanite resembles vadose silt which was deposited in newly emergent Permian carbonates in New Mexico (Dunham 1969). First, caymanite contains only rare recognisable skeletal fragments; diagenetic crystal silt from New Mexico (Dunham 1969) is similarly lacking in skeletal remains. Second, depositional and erosional episodes are manifest in caymanite as cross bedding, parallel laminae and cut and fill structures, while debris fans, cones and high angle floors in vadose silt (Dunham 1969) suggest depositional and erosional episodes. Third, both caymanite-filled cavities and those with vadose silt in New Mexico (Dunham 1969) are commonly filled to the top. Dunham (1969) explained that the absence of voids at the tops of the cavities indicates sediment was deposited from currents rather than downward filtering sediment. More than half of cavities filled with caymanite are filled to the top.

Semeniuk (1971) described diagenetic calcite silt in subaerially leached cavities in Ordovician limestones in Australia. While he compared it with Dunham's (1969) diagenetic crystal silt, this calcite silt might also be compared with caymanite. Semeniuk (1971) hypothesized the calcite silt was deposited in cavities and caves in the subaerial environment. This is the same general interpretation of the origin of caymanite. Davis and De Wiest (1966) pointed out that the phreatic zone experiences only slow lateral groundwater movement. Thus, the phreatic zone would be less likely to produce structures such as cross bedding and channels in laminae of caymanite than the "...aerated vadose zone subjected to periodic heavy precipitation..." (Semeniuk 1971, p. 948).

Caymanite also resembles descriptions of cave sediments in Carlsbad Caverns (Good 1957). Like the caymanite at Pedro's Castle Quarry, the sediments at the Caverns occur beneath layers of flowstone. There are white, brown, black, grey, yellow, and red sediments at Pedro's Castle Quarry and Carlsbad Caverns. Erosion has also produced similarities between localities in that it has made the contacts between laminae irregular. Caymanite sometimes contains alternating laminae of coarse and fine grain sizes (Fig. 3); at Carlsbad Caverns, Good (1957, p. 12) noted that a sample of "...brick-red silt examined under the binocular microscope was found to be composed of sand and silt in alternating layers less than one half inch thick". Cut and fill structures are noted among caymanite laminae (Figs. 10a; 11a - d) and are apparently common in the Carlsbad Caverns (Good 1957). The breccias noted at the bases of some caymanite sequences are believed to be stream cobbles from an underground stream which flowed prior to (in the case of breccias at the bases of caymanite sequences, Fig. 13c) and during (where the cobbles are in and among caymanite laminae, Fig. 10d) caymanite formation. A stream which deposited limestone cobbles in Carlsbad Caverns also eroded sediment and incised trenches into the underlying silt and sand deposits (Good 1957). Finally, the suggestion that the water table provided a stratigraphic control which influenced the positions of some caymanite filled caves on Cayman Island is corroborated by Good's (1957, p. 20) observations that "In addition to phreatic conditions the position of the water table was a very important factor during the formative period" (of the caves).

The conclusion that caymanite was deposited and eroded by two types of stream activity, and that the caves were formed by yet another type of water activity, is congruent with White and Dunn's (1962) work in Jamaica. First, the agents which created the caves on both Grand Cayman and Jamaica were strictly generating new cavities and enlarging others; these waters were not depositing cave sediments. In fact, White and Dunn (1962, p. 21) suggested that the caves were formed by "...sub-water table streams in the shallow phreatic zone..." while the floodwaters which deposited clay sized caymanite must have been of a different stream cycle than those which carried cobbles or cut channels into pre-existing laminae.

After the lithification of the Bluff Formation, caves were created by karst solution at water table level and by leaching of fossils. The spectacular caymanite sequence at Pedro's Castle Quarry, prior to its destruction by dynamite blasting, provided strong evidence that caymanite is a lithified cave or cavity filling sediment. This sequence also contained features indicative of deposition by flowing waters. The information gathered from Pedro's Castle Quarry includes:

1. the sedimentary rocks in the sequence did not completely fill the void, therefore the host rock must have been lithified prior to deposition of the sediments.
2. there were no sediments deposited immediately beneath the roof of the large void, and the roof could be seen to have solution scallops. These scallops are common features of cave roofs and walls (White and Dunn 1962).
3. flowstone was the youngest and stratigraphically highest of the four sedimentary rock types in the sequence. Flowstone is a calcium carbonate chemical precipitate characteristic of the vadose zone in caves (Monroe 1970).
4. the sedimentary structures between laminae of caymanite included cross-laminations, cut and fill sequences and variably thick laminae. Such structures could only have been created by water flowing through the host rock.

Ephemeral, subterranean streams, formed annually on Grand Cayman Island during the rainy season between May and November (Sauer 1982) could have carried and deposited sediment, which formed caymanite. The storms during this season would create high water velocities and hence high sediment carrying capacities when water was channelled through underground cave and cavity systems.

The sediment deposited by these storm generated rivers in the caves would therefore be periodic, having been deposited during regular intervals. During the dry season from December to April, the lamina which had been deposited that year would lithify sufficiently to remain cohesive during the next rainy season, when the underground ephemeral streams formed again. Did more than one lamina form during the same year? Or, perhaps those laminae which are parallel to each other or cross bedded (not laminae deposited before and after an erosional event, such as a channel incision, occurred) were deposited during one season, from the same underground ephemeral river. Certainly some laminae are gradational in colour (Fig. 10d) while others have abrupt colour changes between adjacent laminae (Fig. 10a). Gradational colour changes were deposited from the same river in one cycle.

Approximately 97-99% (by weight) of the caymanite samples is dolomite (Collar 1985, University of Alberta, unpubl.). This dolomite consists mainly of detrital dolomite, which was transported and deposited by the ephemeral, subterranean rivers. Its abraded and anhedral/subhedral morphology suggests it is detrital, although its source was not the Bluff Formation dolostone. Nor is the dolomite a replacement phenomenon of cave sedimented calcite. Since the manganese-consuming bacteria have corroded and replaced dolomite grains, it is obvious that the dolomite was in the cave as unlithified sediment.

Most of the river system dried up between rainy seasons. The bacteria, which were present in those caves and cavities with coloured laminae, require moisture for survival and hence there was probably some (standing) water remaining in the caves. These bacteria became coated by minerals which they derived from either the sediment or the water in the cavities. The coatings of manganese and iron, with traces of nickel and copper pigmented the black, grey, orange, and red laminae. The bacteria could have inhabited the cavities while detrital dolomite was being transported and deposited as cave sediments. Cave inhabiting, manganese associated bacteria, are commonly referred to in the literature (Moore and Nicholas 1964; Moore 1981; James and Choquette, 1984).

VII. DEPOSITIONAL MODEL

The origin of caymanite can essentially be broken down into three parts, namely: (1) where did the sediment that forms the caymanite originate, (2) what mechanism(s) is responsible for the variety of sedimentary structures present in the caymanite and (3) what causes the coloration of the various laminae? Although some problems remain to be solved various lines of evidence can be developed into a model which may explain the varied and complex facts of caymanite formation.

The dolomite in the caymanite is isotopically heavy (Collar 1985, unpubl.), and there are two environments in which this type of dolomite could have formed. The first is a sabkha or any region subjected to high evaporation rates. The second is an area enriched with microorganisms, such as a swamp. There are no sabkhas on Grand Cayman Island and none are recorded in the island's geologic history. There are, however, numerous swamps on the island which are subjected to high evaporation. These swamps are also rich in microorganisms. Collar (1985, unpubl.) argued that swamps, such as that at Hell (Fig. 3) are ideal localities for the origin of the isotopically heavy dolomite. Folk and McBride (1976) also argued that the sediment in caymanite originated in the swamps.

The biological process of methanogenesis could occur in swamps and ponds of stagnant water, where microorganisms flourish. This process results in the production of methane, water, and carbon dioxide by the destruction of organic matter. "During this process the microorganisms fractionate the heavier isotopes into carbon dioxide. Methanogenesis will therefore cause a sharp increase in the delta values of the carbonates precipitating in this water..." (Collar 1985, unpubl., p. 25). Methanogenesis may be occurring in these fresh water swamps that have odorous sediments on the bottom. Samples of these muds were collected and analysed by Collar (1985, unpubl.). The isotopic analyses of the dolomites from the muds at Hell swamp showed that while they are heavy, they are slightly lighter than the dolomite in the caymanite. Collar (1985, unpubl.) explained that isotope values would turn out to be lighter in the tests than they actually are because of an analytical difficulty. "Since the Hell dolomite values are probably only minimum values, the Hell dolomites should actually plot closer to, or within, the caymanite field" (Collar 1985, unpubl. p. 28). Thus, this environment is a suitable place for the nucleation of the dolomite comprising caymanite.

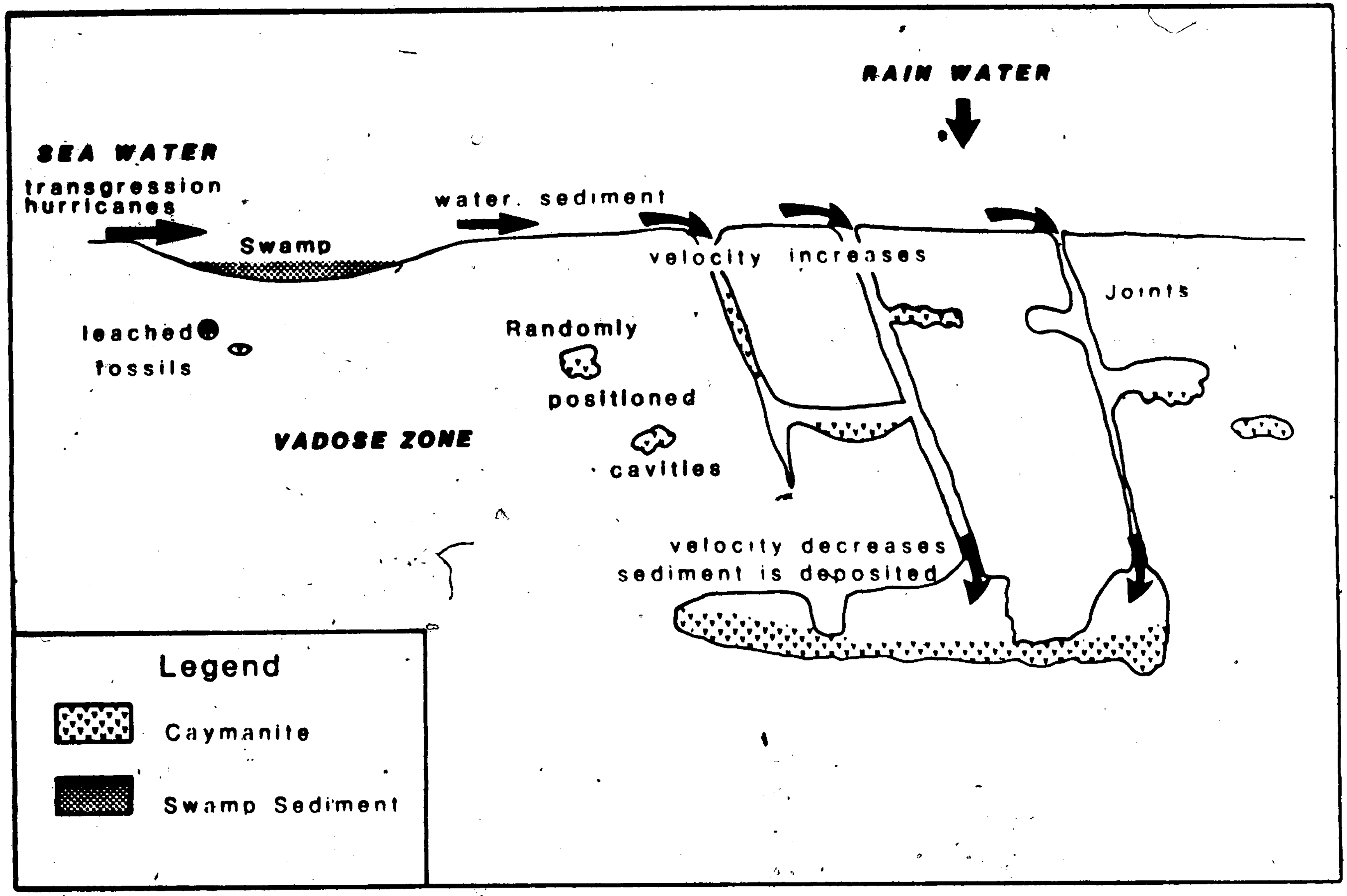
Microcrystalline dolomite in the swamp mud from Hell comprises 70% of the less than 5μ size fraction, and yet only 5% of the bulk sample (Collar 1985, unpubl. p. 26). Considering the similarities of isotopes and sizes of dolomite, it is possible that the dolomite in the swamps was the source of the dolomite in the caymanite. The proportion of dolomite in caymanite is much higher than in the sediments from Hell; thus, the microcrystalline dolomite must have become concentrated prior to its deposition in cavities as caymanite.

An effective mechanism of eliminating nondolomite material would be during the transportation stage, when swamp sediment was carried into the karst tunnels and cavities by seasonal rivers (Fig. 23). The dolomite was the smallest grain size and thus would have been transported in larger amounts than coarser grain sizes, and also would have been transported farther into the karst system. The coarse grained fraction contains mostly aragonite (87% of the bulk sample), some calcite and minor dolomite (Collar 1985, unpubl., p. 26). During exceptionally turbulent periods, when hurricanes generated higher water volumes and velocities, coarse-grained material including sand and pebble-sized fragments could have been transported into the caves and cavities.

There are two problems with this model. First, associated with water passing through the karst system, the currents would probably be capable of transporting grain sizes larger than 5μ. This would be especially true during hurricanes and the annual rainy season when vast amounts of water are available and capable of transporting coarser grain sizes than are present in caymanite. Second, SEM examination of sediment from the swamp at Hell a) showed very little dolomite and b) bore little resemblance to material in the caymanite. It is, however difficult to compare the modern swamp sediment which is rich in organic

Figure 23

Schematic diagram (not to scale) of possible origin of caymanite. Sea and rainwater transport dolomite from swamp sediments down joints into karst cavities and caverns and leached fossils. Depositional structures form in the caymanite because of current transportation in the vadose zone.


SEA WATER
transgression
hurricanes
Swamp
water. sediment
RAIN WATER
velocity increases
Joints
leached fossils
Randomly positioned cavities
VADOSE ZONE
velocity decreases
sediment is deposited
Legend
Caymanite
Swamp Sediment

material and other material (which would not survive lithification) and the lithified caymanite. One would expect a greater degree of similarity between the two if the swamp sediments were the source of caymanite dolomite. It is possible, however, that the original sediment in the cavities was later modified by diagenesis to form caymanite as we now know it.

A. DEPOSITIONAL EVENTS

The filling of cavities in the Bluff Formation with caymanite involved both deposition and erosion. A depositonal event is defined as the time during which one lamina of caymanite was deposited. Sedimentation was achieved by water moving through cavities in the vadose zone. Dunham (1969) also noted that a similar process was involved in the formation of laminated vadose crystal silt in Townsend Reef, New Mexico. Sedimentation varied with respect to water velocity, grain size being transported, the sediment load and the rate of deposition. Variations in these parameters lead to variability in grain size, laminae thickness, laminae attitude as well as formation of depositional structures such as cross bedding, parallel laminations and graded bedding. Dunham (1969) attributed cross-bedding and very high dip angles to vadose sedimentation, but did not elaborate on any changes in the system which would yield such changes in the characteristics of the laminae. Bathurst (1975) concurred with Dunham (1969) yet did not develop the concepts further. Obviously, the zone of sedimentation and the water carrying the sediment must have undergone some fluctuations in order to produce cross-laminations, high-angle dips and graded bedding.

Modification of the sediment already deposited was achieved by erosional events. Factors controlling the degree of substrate modification include:

1. the degree of lithification of the substrate prior to erosion; this in part would have been a function of the time interval between deposition and erosion.
2. the velocity of the waters moving through the cavity. The most common features produced during these erosional events were channels (Figs. 5, 12a). Such channels were later filled during the next depositional event.

Deep channels (Fig. 5), such as that in one sample from Blowholes probably represent a high velocity stream which was capable of extensive downcutting. Conversely, a shallow channel may indicate a less powerful stream that was moving slowly. A shallow channel may also signify one that was not eroded for as long as the deeper one.

Depositional events appear to have been more common than erosional events. During depositional events, detrital dolomite was transported from the surface through underground streams into cavities in the Bluff Formation (Fig. 23). The paucity of euhedral crystals, and abundance of anhedral dolomite grains (Fig. 17a) attests to their transportation. Vadose silt in the Townsend Reef (Dunham

1969) was transported from the subaerial surface into the vadose zone by moving water. The karst and joint systems in the Bluff Formation provide an ideal subterranean network of channels through which rainwater and seawater could move (Fig. 23). This would be especially true during storm periods (particularly hurricanes). It seems probable that seawater would also be driven into such subterranean systems during periods of hurricanes, since it is known that seawater does innundate parts of the island. It is these seasonal waters, with fluctuating velocities and volumes which transported and deposited the detrital dolomite which later formed the caymanite.

Three processes were concomitantly involved in the formation of a caymanite lamina, namely (1) deposition; (2) formation of sedimentary structures and (3) pigmentation.

1. *DEPOSITION*: each lamina of dolomite appears to be the product of one depositional event. Deposition may have occurred progressively as the waters moved through the cavities. It seems more probable, however, that deposition occurred very rapidly in the waning stages of the flood event. That deposition occurred from moving waters was demonstrated by Dunham (1969) who described similar, laminated filled cavities in New Mexico. Most of the laminated cavity fills that he examined were completely filled, and no voids existed at the top of the cavity. The cavities could not have been "... filled to the top by simple infiltering " (Dunham 1969, p.

160).

2. *SEDIMENTARY STRUCTURES*: During deposition of the sediment a variety of sedimentary structures developed. Four types of sedimentary structures occur in caymanite: (1) cross-laminations; (2) parallel laminations; (3) graded laminations and (4) channel filling laminae. Where conditions remained constant in a cave or cavity throughout depositional events, thin laminae were deposited parallel to their predecessors. In an apparently similar depositional environment Dunham (1969) and Bathurst (1975) also noted the presence of cross laminae, parallel laminae, and steep dip directions. Some larger sequences show remarkable lateral continuity among their laminae (Fig. 6a). However, if the morphology of the cave stream's channel changed or traction loads were involved, cross-laminations resulted (Fig. 7). When coarse material was included in the sediment load, graded bedding resulted. Graded bedding is, however, rare in caymanite. If channels had been eroded into previously deposited caymanite laminae, successive depositional events served to fill those channels.

3. *PIGMENTATION* of a lamina occurred as bacteria, living in, or transported into the cave, oxidized manganese and iron, along with minor amounts of nickel and copper. These metals were transported into cavities in very small amounts (Table 1), either contemporaneously with

the dolomite, or after the dolomite was deposited, with groundwaters that had passed through terra rossa soils. The terra rossa soils are the only known source of the metals (Table 1), and occur on the surface of the island or in pockets in the Bluff Formation. The bacteria oxidized the metals for energy, and these processes in turn coloured laminae black and grey (manganese rich) and red and orange (iron rich). If no bacteria were present then the sediment remained white. Pigmentation of sediment by bacteria is a common phenomenon (Foster 1949, Murray 1954, Broughton 1971, and Hill 1976).

Continued deposition of sediment resulted in progressive stacking of different coloured laminae. For example, the formation of coloured cross-laminations, gradational boundaries, and parallel laminations each represent different depositional environment conditions. Therefore each depositional event was also unique. As laminae were deposited in different forms, bacteria still pigmented many of them. The combination of variable characteristics of the depositional system: metal oxidizing, sediment pigmenting bacteria, and development of depositional structures produced caymanite in cavities and caves.

B. TIME

The timing of the various depositional and erosional events is of paramount importance. Folk and McBride (1976) did not account for the repetition of events in their description of how caymanite formed: a marine transgression, causing "... black, stinking mud..." (p. 667) to filter through the karst system does not adequately explain the laminations in caymanite. The duration of sedimentation would obviously have influenced lamina thickness. Also, a large volume of water, carrying a large sediment load, would generate a thicker lamina than a smaller volume of water. The time between depositional events would have influenced the degree of lithification. This in turn would have partly controlled the effect of succeeding erosional events.

The consistency in the appearance of laminae in any caymanite sample is important. While the minute details differ, the rock usually comprises a series of thin, evenly coloured laminae of relatively uniform thicknesses. Had the duration of depositional events or the volume of water and corresponding sediment load changed with each subsequent event, the laminae would be of different thicknesses.

Erosional channels provide convincing examples that the laminae were sufficiently lithified prior to erosion so that, when the channel was carved, slumping did not occur. The channels present in GC 83 526 (Fig. 5) have very steeply dipping sides (up to 35°), which are beyond the angle of repose unless laminae were partly lithified. Certainly they were not fully lithified or seasonal erosion would not have been feasible. Dunham (1969) observed steeply dipping (up to 40°) floors in cavities filled with vadose crystal silt. Although he did not discuss the stability of such laminae prior to lithification, he noted that the tectonic dip on the Townsend Mound was only 2° (Dunham 1969, p. 151), thus the high-angle dips were sedimentary. GC 83 480, from the east end of the island, contains an erosional channel that was never completely filled (Fig. 12a) and thus, the caymanite is geopetal. Erosion of small pockets of caymanite (Fig. 5), and subsequent deposition of a younger phase of caymanite, occurred in another sample.

Very coarse sand to pebble sized, subangular to subrounded, dolostone fragments from the Bluff Formation were rarely incorporated in the caymanite deposits (Figs. 11d; 14c, e). These may have originated by collapse and breaking off of pieces from cave roofs, or they may have been transported into the caves by the karst streams. Limestone and dolostone pebbles and fragments lining cave streams are common (Moore and Nicholas 1964; Potter and Rossman 1979). Since some fragments in caymanite are rounded (Fig. 11d) it would suggest they were reworked by the streams. The irregular occurrence of these conglomeratic stream deposits indicates periodic high velocity currents. Some of these fragments are coated with a thin black manganese rich coating (Figs. 11d; 14c, e). These are similar to the coatings observed by (Broughton 1971; Bull

1983). Apparently these coatings developed after the fragments were deposited; in one example (Fig. 11d) the coating on a pebble extended downward only to the level of a black lamina. This suggests that the dolostone was partly buried in caymanite and became coated with manganese as the black lamina formed.

The annual five month rainy season between December and April (Sauer 1983) would be a reasonable time for the origin of these laminae. During these months high volumes of rainfall would rush down the joints and through the karst cavities and caves depositing and eroding microcrystalline dolomite (Fig. 23). The volume of water would determine the velocity of the underground streams, and the length of time that sediment would be deposited. During periods of exceptionally high rainfall when velocities were also high, coarser grain sizes, such as those fragments from the Bluff Formation, could be transported and deposited by the cave streams.

C. EROSION

Erosional events are also evident in caymanite. Erosion is evident between generations (groups of laminae with similar characteristics) by channels. There is no detectable pattern of erosion: some samples (Fig. 6a) have no evidence of erosion while other samples (Fig. 5) contain considerable evidence of erosion. Thus, erosion did not occur regularly after the deposition of each lamina, or even after a certain number of laminae. This concurs with the suggestion that seasonal hurricanes may have been responsible for the deposition of laminae, and high velocity currents during hurricane or exceptionally rainy seasons caused erosion of laminae and deposition of coarse-grained fragments (Fig. 23).

There are two possible relationships between the water which caused erosion and that which resulted in the deposition of the dolomite, namely: (1) the erosional currents were entirely separate from the depositional ones, and (2) the erosion occurred during a high velocity period of the current, which later slowed to the velocity required to deposit the fine dolomite grains. Evidence supports both possibilities. In one sample (Figs. 12c, d) a channel in caymanite has been filled with both coarse and fine grained sediment. The interpretation of this sequence is that a high velocity current eroded a channel into previously deposited laminae, and as the current slowed it deposited material of decreasing grain sizes. A second sample (Fig. 11a) also has a channel but one which has been filled only with caymanite and no coarse grained material. This may represent a situation where one current carved the channel while a second current, much more lethargic than the first, deposited the channel-filling sediment.

VIII. CONCLUSIONS

Caymanite has been examined macroscopically, microscopically and chemically. Although some questions remain to be answered, the following important conclusions can be made:

1. Caymanite is a multicoloured laminated dolostone that occupies cavities in the Oligocene Miocene Bluff Formation. The cavities and caverns were created by leaching of fossils and by karst solution processes.
2. Caymanite is composed of very small anhedral crystals of dolomite, rare calcite, and traces of aluminium rich particles. The coloured laminae also contain manganese, iron, and minor nickel and copper.
3. The dolomite may have been derived from sediments that are forming and accumulating in the swamps on the island.
4. The metallic minerals occur as precipitates coating spherical bacterial colonies and rod-shaped bacteria. These are the colouring agents of the red and black laminae. Bacteria living in the cavities during the time of formation of caymanite oxidized and precipitated the metals.
5. The manganese, iron, nickel and copper in the caymanite probably originated in the terra rossa soils. Groundwaters brought the metals into the cave sediments.
6. The dolomite was transported to the cavities via a well developed system of joints and fractures into the

caverns, cavities and leached fossils in the vadose zone.

7. Rain and seawater carried the dolomite into the karst system. Because of the large volumes of water involved and high velocities, hurricane seasons are probably periods when caymanite would have been deposited.

Problems associated with the origin of caymanite that remain to be answered include:

1. The age of caymanite: did it all form at one period in geological history or did it form by an ongoing process that is still operative today.
2. The mechanism by which the fine dolomite grains were concentrated from highly variable swamp sediment.

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